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The 275 kV 'English Electric' air-blast circuit-breaker and current-transformers at the West Melton substation of the Central Electricity Authority's Yorkshire Division

Operating Experience with an 'English Electric' 275 kV Air-blast Circuit-breaker and Current-Transformers at West Melton

By P. MORETON, Switchgear Design Department, and E. J. MELLOR, Instrument Transformer Design Department.

THE REASONS FOR the creation of the 275 kV 'supergrid' by the Central Electricity Authority have been widely published, notably in the paper read before the Institution of Electrical Engineers by D. P. Sayers, J. S. Forrest and F. J. Lane, entitled '275 kV Developments on the British Grid System'*

Prior to the adoption by the (then) British Electricity Authority of the report of the Committee investigating the scheme, and the authorisation in July 1950 of the construction of the first section of the supergrid, work had been proceeding on the erection of a trial section between Staythorpe, near Newark in the East Midlands Division, and West Melton near Sheffield in the Yorkshire Division. This section of the supergrid was inaugurated by Sir John Hacking, then Deputy Chairman (operations) of the Authority, on 15th July 1953, and consists of a single-circuit overhead line with twin 0·175 sq in conductors connected with the 132 kV grid by means of a 120 MVA 3-phase auto-transformer at the substation at each end of the line.

The equipment originally ordered for each of the substations consisted of one 120 MVA 132/275 kV auto-transformer and a 275 kV isolating switch together with the necessary copperwork and insulators to connect this equipment to the 275 kV line and the existing 132 kV switchgear. The transformer for the West Melton substation was supplied by The English Electric Company. The full 275 kV substations were ordered later and were not due for commissioning until late in 1955.

* *Proc. I.E.E., Part II, December 1952.*

Meanwhile, The English Electric Company had been developing a 275 kV 7,500 MVA air-blast circuit-breaker and current-transformers to meet the technical requirements laid down by the Authority.

Following successful tests on a single-phase prototype, a three-phase breaker was built and it was evident that testing of this unit would be completed early in 1953. The Authority therefore agreed to allow the installation of this breaker, together with three current-transformers, in one of the substations, so as to obtain as early as possible operational experience with a 275 kV circuit-breaker, which would be of considerable benefit both to the Authority and to this Company.

West Melton was chosen as the more suitable site and the circuit-breaker together with the three current-transformers, the compressed air equipment and a remote control panel was installed and commissioned early in July 1953. This equipment was in service during the inauguration ceremony on 15th July, and was inspected by a large party of engineers who visited the substation.

Since that date the breaker and current-transformers have been in continuous commercial service and have also been subjected to special tests. The purpose of this article is to describe briefly the equipment concerned, the tests and the results of this very valuable operating experience which now extends over more than two years at a voltage higher than any for which British switchgear has previously been installed.

It should be mentioned here that the installation of this breaker at West Melton is of a temporary

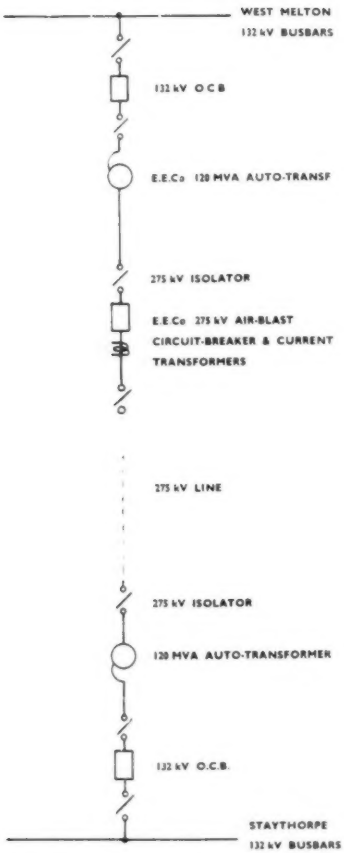


Fig. 1.—*Diagram of the West Melton - Staythorpe 275 kV interconnection*

nature, as this is not one of the substations allocated to The English Electric Company. The breaker will therefore be removed when the substation is completed, and by that time the experiment will have fully served its purpose of proving the performance of this equipment under actual service conditions, and the soundness of the requirements specified by the Authority.

Fig. 1 shows the diagrammatic arrangement of the complete circuit.

I. AIR-BLAST CIRCUIT-BREAKER

Description

The arrangement of a single pole is shown in Fig. 2 and consists of two separate columns each comprising an air receiver and supporting column with associated interrupters and diverters.

The air receiver is designed to cover the most stringent requirements of all the leading insurers and to provide the facilities they require for inspection under the Factories Act.

Porcelain insulation is used throughout, both for the major insulation of the column and what may be called the minor insulation for the interrupters and surge diverters.

The main column forms a tripod supporting structure with a central porcelain column which feeds high pressure air from the blast valve at the base up to the interrupters.

Special design features are incorporated in each leg of the tripod structure to ensure that negligible pre-stressing takes place in the porcelain insulators during the assembly of the breaker, and to give flexibility during operation, thus preventing undue stress in service.

Positive drive to auxiliary switches for breaker position indication etc. is effected by drive rods through the insulators of one column, as can be seen on the cross-sectional drawing in Fig. 2.

The mechanism housing at the top of the tripod structure contains the closing and opening air-engines for the make switch blades.

Interrupters are of the axial blast type, and in parallel with each interrupter are connected porcelain clad non-linear resistance units. These resistances perform two main duties ; (1) to ensure equal division of restriking voltage when interrupting current, thereby achieving maximum breaking rating and efficiency, and (2) to limit the value of overvoltage when switching small currents at low power factor, when current-chopping may take place.

Although the three-phase breaker consists mechanically of six separate columns, electrical and pneumatic interlinkage of all the auxiliary operating gear gives complete and positive operation and ensures that three-phase tripping or closing is obtained in the unlikely event of a fault developing on individual control valves.

Every consideration has been given in the design to afford ease of maintenance, and inspection of

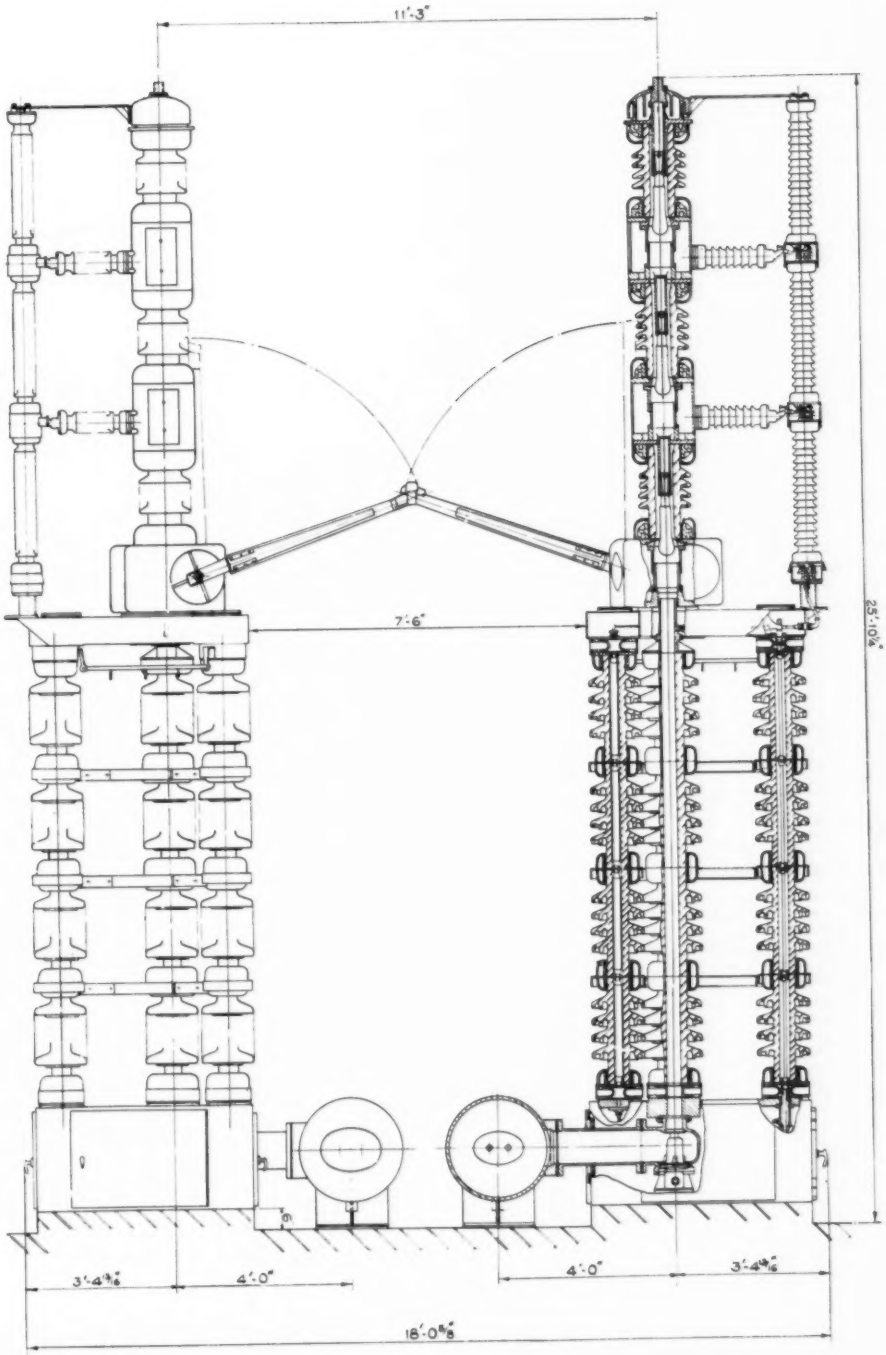
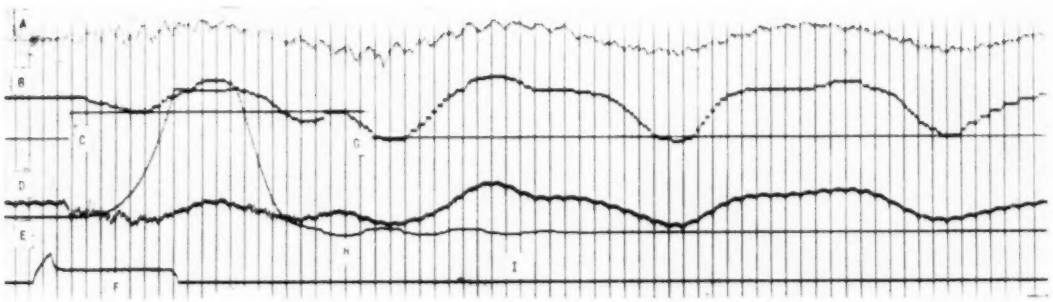


Fig. 2.—Single-pole arrangement of 275 kV air-blast circuit-breaker



A. Stress at bottom of column
B. Mechanism housing deflection
C. Interrupter contacts part
D. Stress at centre of column
E. Make-switch blade travel at start
F. Trip coil current
G. Interrupter contacts reclose
H. Make-switch blade travel at finish
I. Oscillogram for trip operation with initial air pressure 300 lb sq in

Fig. 3.—Typical oscillogram showing mechanical strains during opening operation

the interrupters can be easily carried out in the minimum of time.

Type Tests

On completion of the prototype a very comprehensive series of type tests was undertaken to cover all possible conditions which might obtain in service, and to prove the breaker performance under these conditions.

The following brief résumé of these type tests will serve to illustrate the considerable amount of development which is necessary before a breaker of this type is offered for service.

Air-flow Tests

This work is an early essential in the development of the air-blast breaker and was divided into two groups, the first being continuous flow testing with mass flow related to the breaker constants, and the second the study of wave action under transient air-flow conditions.

These investigations were made in the Air-flow Laboratory of D. Napier & Son Ltd. Special models were made to the proposed design, and the improvements resulting from the tests, to give better aerodynamics and high interrupting performance, were incorporated in the prototype.

Strain Gauge Measurements

The support column was initially subjected to static cantilever pull tests at varying loads and the stresses in the porcelains at different locations measured with resistance strain gauges.

After the buffering tests had been completed on the air-engines driving the make switch blades, dynamic strain gauge measurements were obtained on a cathode-ray oscillograph during closing and opening operations. A typical oscillogram showing strains at a few points is reproduced in Fig. 3.

Timing and Buffering

Duddell oscillograph records were taken over the range of 200 to 330 lb/sq in (the normal operting pressure is 300 lb sq in) and covered interrupter and make-switch timing coupled also with the travel of these units to establish that the buffering was correct.

Endurance

A mechanical endurance test of 1,000 operations was carried out and oscillograph records taken at intervals to indicate any variation in performance.

Heat Run

Thermo-couple and thermometer readings were recorded during a heat run to prove the current-carrying capacity of the breaker up to 1,200 amperes over a period until the temperatures were steady under this condition.

High Voltage Impulse

A series of tests was performed and the required withstand level of 1050 kV was obtained by means

of shaped electrodes and screening at highly stressed points. Five positive and five negative shots withstand were taken with a 1/50 microsecond wave.

The co-ordination of the insulation level between the interior and exterior of the porcelain insulators of the main column was proved by raising the test voltage above 1,050 kV until flashover was observed on the outside of these insulators.

High Voltage Test

A test voltage of 485 kV at 50 cycles was applied for 1 minute, to earth, between phases, and between the terminals of one pole.

Corona Onset

Tests were carried out in complete darkness to prove that no corona was visible on the breaker at 220 kV.

Wet Flashover Test

The required minimum figure of 460 kV for 30 seconds was obtained.

Cold Test

A single-phase unit was subjected to tests in the cold chamber of the Nelson Research Laboratories at Stafford.

Timing oscillographic records were obtained with temperatures ranging from + 20°C to −20°C, and also at air pressures below the lock-out pressure of 230 lb/sq in to prove an adequate safety factor.

Following these tests, ice was formed on the breaker as shown in Fig. 4 and breaker performance proved for opening under these conditions by a number of operations.

Voltage Distribution

To prove that uniform voltage distribution was obtained by means of the non-linear resistance diverters, tests were carried out under impulse and low frequency voltage conditions.

Short Circuit

Comprehensive tests were carried out in the Nelson Research Laboratories to prove a rating of 7,500 MVA at 275/300 kV. Breaking tests included unit tests with single-phase shots on one interrupter in order to obtain maximum proof of the breaker short-circuit rating.

Fig. 4.—A single-phase unit of a 275 kV air-blast circuit-breaker undergoing tests in the cold chamber at the Nelson Research Laboratories

Porcelain Insulators

Temperature cycle tests were undertaken on all the types of insulators incorporated in the design, consisting of immersion in hot water and cold water baths with the specified temperature difference. The series of tests on each porcelain comprised three transfers from cold to hot, twice from hot to cold, with a period of 1 hour between transfers.

Installation

The circuit-breaker was installed in June 1953 and was the first in service at 275 kV in Great Britain. It is shown in the frontispiece with the overhead line tower in the rear.

As previously mentioned, this breaker controls the 275 kV transmission line approximately 41 miles long which links the 132 kV network of the

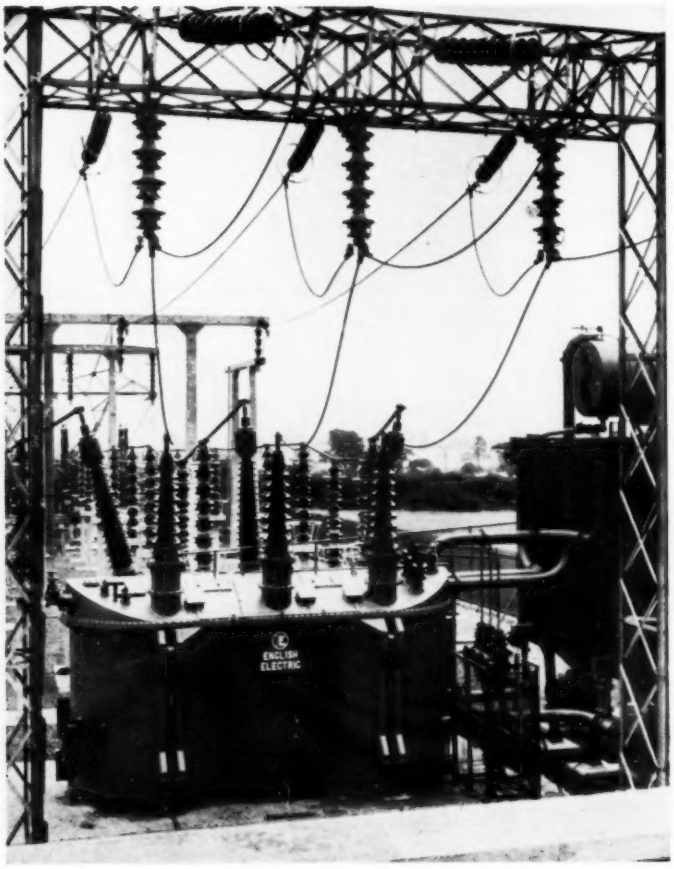


Fig. 5.—The 120 MVA 275/132 kV 'English Electric' transformer at West Melton

Yorkshire Division at West Melton with the 132 kV network of the East Midlands Division at Staythorpe, and therefore forms a very important link in the power system of the grid.

The step down in voltage from 275 kV at West Melton is by means of the 120 MVA 'English Electric' power transformer shown in Fig. 5.

Fig. 6 is a side view of the breaker, the local control cabinet for which can be seen in the left-hand corner of the enclosure, directly behind this being the compressor house.

The current-transformers, which are described later, can be seen in the foreground of Fig. 7.

The air supply equipment consists of 3-stage air-cooled compressor units delivering air at 600 lb/sq in to the indoor high pressure receiver on which the compressors, motors, control gear, etc., are mounted. From this receiver air is passed to an outdoor receiver also at 600 lb/sq in so that fully effective cooling lowers the dew point and removes the danger of moisture in the breaker on expansion to the normal operating pressure of 300 lb/sq in.

Adequate filtering is included to prevent damage to the metal-to-metal valve seats used exclusively in this design.

In the commissioning tests oscillograph records were taken covering all mechanical operating conditions of the breaker and were in fact a repetition of those described as 'Timing and Buffering' under the previous heading of 'Type Tests'.

Line and Transformer Switching

Tests were carried out before the breaker was put into service and oscillographic measurements were made by a team from the Nelson Research Laboratories to determine the amplitude of the transient overvoltages at the transformer and circuit-breaker terminals during switching operations. The measurements recorded under various switching conditions were as follows and catered for all service requirements :—

(*a*) The transient voltages and current in the power transformer when energised and de-energised from the 275 kV system by means of the air-blast circuit-breaker with the 132 kV winding of the transformer unloaded.

(*b*) The transient voltages at the terminals of the air-blast circuit-breaker and the line current at West Melton when the transmission line is switched by the air-blast circuit-breaker with the line open-circuited at Staythorpe.

(*c*) The transient voltages at the terminals of the air-blast circuit-breaker and the line current at West Melton when the transmission line is switched by the circuit-breaker with the 120 MVA transformer at Staythorpe connected but the 132 kV winding of this transformer unloaded.

The highest transient overvoltage produced during all the above series of tests was 2·2 times the normal 50-cycle phase peak voltage, and twice normal was only exceeded on three occasions, the majority of tests producing an overvoltage factor of not more than 1·4. A representative selection of test results is given in Table I.

On no occasion did flashover take place on the co-ordinating gaps of either the 275 kV or 132 kV side.

These results indicate that no undue stressing of the system would occur by reason of the air-blast circuit-breaker operation.

II. CURRENT TRANSFORMERS

Simultaneously with the development of the air-blast circuit-breaker, design work had commenced on a suitable 275 kV current transformer which due to the double column construction of the breaker had necessarily to be a separate unit.

A prototype was built and tested and at about this time the (then) British Electricity Authority requested that manufacturers should co-ordinate their designs so that they would be interchangeable. This requirement was confined to the relative positions and sizes of the primary terminals, secondary terminal box, cable glands and the base fixing holes.

It was found that the 'English Electric' prototype had much in common with the ideas of certain other prominent manufacturers and consequently it was possible to arrive at an early agreement. Furthermore, by making only minor design changes, a common high-voltage porcelain was agreed upon with two other current transformer manufacturers.

Specification

The following specification was agreed between the Authority and interested manufacturers.

Secondaries

Five cores and secondary windings to be accommodated, namely :—

2—for bus zone protection, ratio 600/1 amp.

2—for overcurrent protection and instruments, ratio 600/1 amp

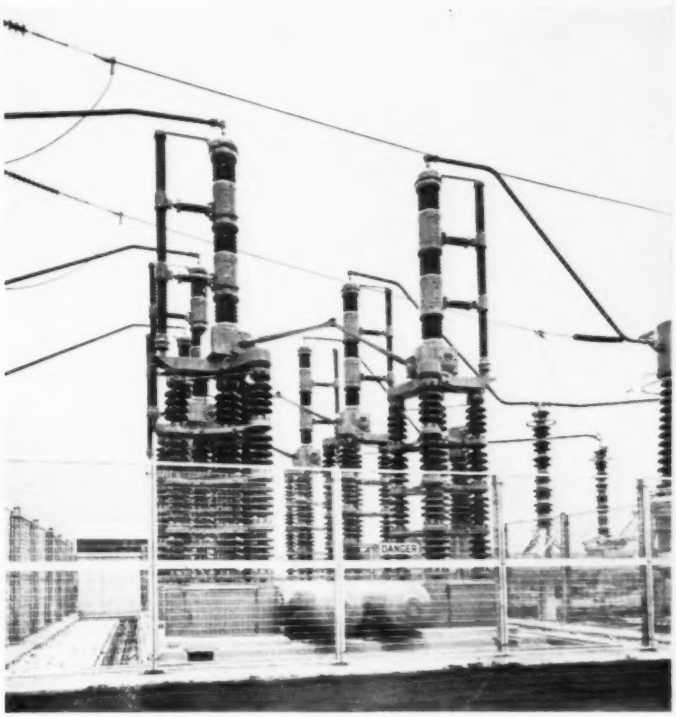


Fig. 6.—Side view of 275 kV circuit-breaker at West Melton, with local control cabinet on left

TABLE I.

TEST RESULTS OF TRANSFORMER AND LINE SWITCHING BY 275 kV AIR-BLAST CIRCUIT-BREAKER

Switching Condition	Test No.	Duty Cycle	Peak 50 cyc phase voltage kV			Switching Overvoltages					
						Peak transient voltage, kV			Overvoltage factor		
						R	Y	B	R	Y	B
a) Energising and de-energising 275/132 kV auto-transformer	19	M		251		221	219	314	·88	·872	1·25
	20	B		237		233	233	288	·982	·982	1·21
	23	M		235		238	213	333	1·01	·905	1·42
	24	B		233		224	203	249	·960	·870	1·07
	29	M		235		259	221	270	1·1	·941	1·15
	30	B		233		275	297	282	1·18	1·27	1·21
			R	Y	B						
(*b*) Energising and de-energising open-circuited transmission line	31	M	221	218·4	224·5	334	318	352	1·51	1·46	1·57
	32	B	221	220	226	255	215	173	1·15	·980	·765
	33	M	224·5	221	224·5	357	318	400	1·59	1·44	1·78
	34	B	222	221	225	320	485	393	1·44	2·2	1·75
	37	M	224·5	220·7	228	344	379	395	1·53	1·72	1·73
	38	B	223	220·3	224·5	240	263	230	1·08	1·19	1·02
	44	B	229·8	227	231·6	303	240	474	1·32	1·06	2·05
(*c*) Energising and de-energising transmission line with open-circuited auto-transformer at Staythorpe	48	B	231·5	226·2	229·6	343	452	357	1·48	2·00	1·55
	49	M	229·6	224·5	229·6	371	288	320	1·61	1·28	1·40
	50	B	230	227	230	332	314	238	1·44	1·38	1·04
	51	M	227·2	224·7	228	280	226	390	1·23	1·01	1·71
	52	B	229·8	226	230	286	330	312	1·24	1·46	1·36
	53	B	228	226	228	235	227	290	1·03	1·01	1·27

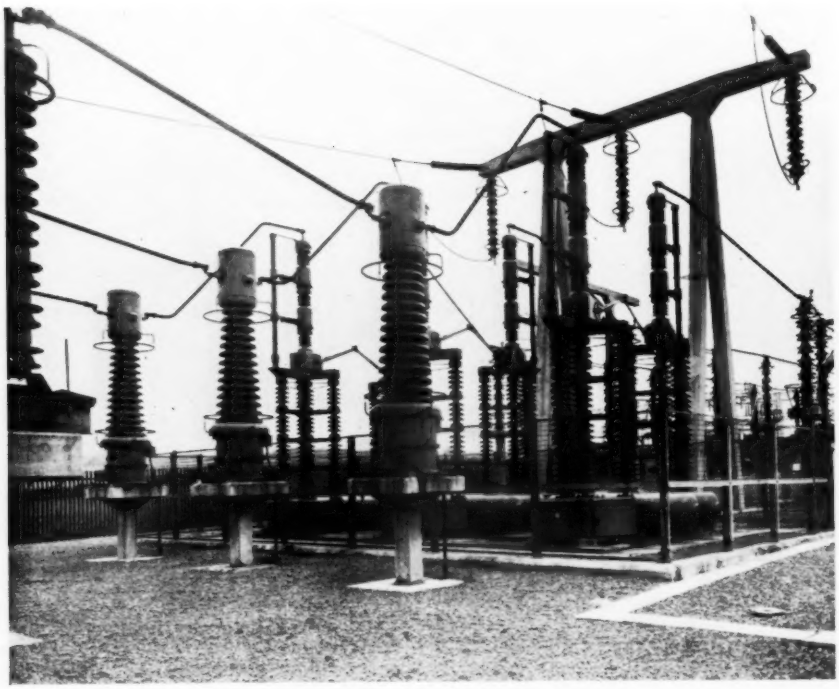


Fig. 7.—The 275 kV current-transformers at West Melton, with the air-blast circuit-breaker behind

1—for feeder or transformer protection, ratio 600/300/1 amp.

All secondaries must be capable of working continuously at a ratio of 1,200/2 amp.

Primary

Insulation :

Continuous system voltage ..	300 kV max.
Power frequency test voltage for 1 minute, dry	485 kV
Power frequency test voltage for 30 seconds, wet ..	460 kV
Impulse voltage withstand (full wave)	1,050 kV peak
Voltage below which corona is not to occur, dry	220 kV
Minimum total external leakage distance over porcelain	275 in
Minimum protected external leakage distance over porcelain	138 in
Continuous primary current ..	1,200 amp max.
Short-circuit current for 3 seconds	16,000 amp

General

Frequency	50 cyc
Generally to B.S. 81 : 1936 and B.S. 2046 : 1953.	

General Description

The complete current transformer is shown in Fig. 8. It is an oil filled unit for outdoor service.

High Voltage Winding

The H.V. winding incorporates a hair-pin tube having graded insulation consisting of oil-impregnated crêped cable paper in which metal foils are interposed at intervals (Fig. 9).

The outermost of these foils is connected to earth via an insulated terminal and link. This arrangement enables a periodical check to be carried out on the major insulation.

The ends of the tube are connected to the H.V. terminals, the joints between which and the top housing are protected from the weather.

A spark gap is fitted across the H.V. winding as protection against voltage surges, and is situated between the top housing and the insulated terminal.

Cores

The cores are of the jointless ring type, made from high grade cold-rolled silicon steel. Precautions are taken to prevent local core saturation.

Secondary Windings

The five cores and secondary windings are supported from the tank top plate (Fig. 9). The toroidally wound secondary windings are brought out through porcelain insulated terminals into a L.V. terminal box on the side of the housing. The

Fig. 8.—A complete 275 kV current-transformer

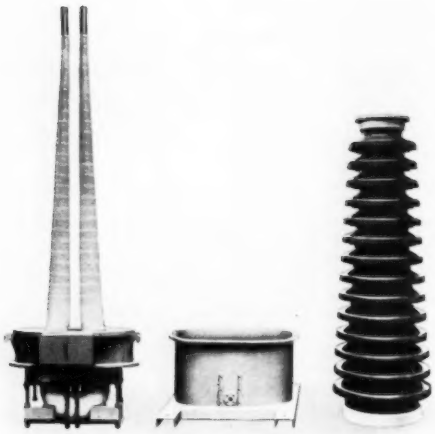


Fig. 9.—The H.V. winding, tank and porcelain insulator of a 275 kV current-transformer

arrangement is such that the secondary windings will withstand the resultant voltage when left open-circuited and full load current is passed through the primary for one minute. The L.V. terminal box is fitted with an easily removable weatherproof slide-on cover.

Housing

The cores and secondary windings are housed in a welded steel tank which also forms the base of the transformer. The H.V. 'hair-pin' passes through the ring-type secondaries in the lower metal housing, and the legs are encased in a shedded porcelain.

Oxidation of the oil and absorption of moisture by the major insulation is prevented by an oil-trap seal which forms the top housing. The construction is such that the insulating oil in the main chamber cannot come into contact with the atmosphere, neither can pressures nor depressions be created due to temperature variations. The principle on which this seal operates is shown in Fig. 10.

Processing

Since the satisfactory operation of this equipment depends to a large extent upon the dielectric strength of the oil-impregnated cable paper, a very exacting method of processing has been developed which maintains careful control of the dielectric loss angle.

The insulation is dried out after complete assembly, first at atmospheric pressure, followed by a period under a high degree of vacuum. When thoroughly dry, oil to B.S. 148 : 1951, which has been filtered and de-gasified, is drawn into the housing without breaking the vacuum. Finally a period of soaking is allowed.

Tests

One current transformer was subjected to a full set of witnessed type tests to prove compliance with the specification of the British Electricity Authority. The remaining two transformers were subjected to routine tests only.

III. SERVICE EXPERIENCE

Circuit Breaker

Since the air-blast circuit-breaker was fully

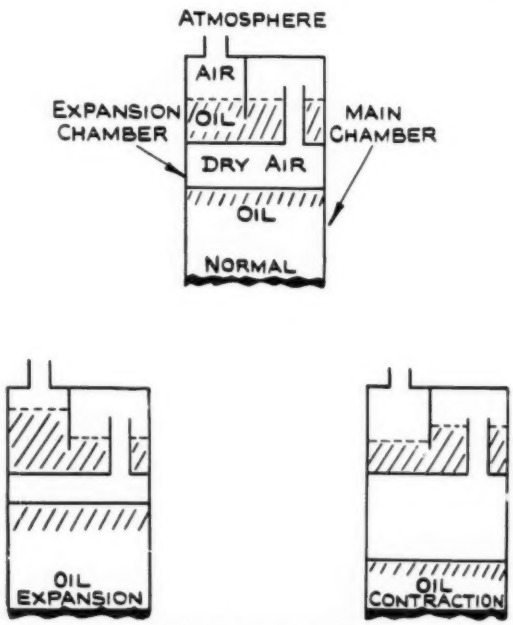


Fig. 10.—Principle of operation of oil-trap seal for current-transformer

commissioned and went into service in mid-July 1953, it has performed satisfactorily, having been in continuous use apart from normal maintenance.

Switching operations in this period have covered satisfactorily fault clearances, load switching up to 100 amperes, and line or line and transformer switching.

All weather conditions have been encountered and in these the design proved satisfactory.

Current Transformers

The current-transformers installed with the 275 kV air-blast circuit-breaker have given similar service devoid of any trouble.

Valuable information can be gained from service experience with current-transformers of this type on the behaviour of the major insulation and the exclusion of moisture from the main oil chamber. The extensive tests carried out in the prototype stages were checked on two of these current transformers after approximately twelve months in service.

Dielectric loss angle tests were made and the results compared with those obtained before despatch to site, but the testing equipment limited the site tests to a maximum of 15 kV whereas the works tests were taken up to 190 kV. The Schering Bridge and equipment used for both works and site tests were substantially the same, so that any difference introduced as a result of minor changes can be considered negligible.

A comparison of the results given in Table II shows a slightly lower power factor for the readings taken on site. This would indicate that the major insulation after twelve months service is better than when it left the works and is possibly due to the additional soaking period, the values probably stabilising a short time after delivery of the current transformers to site.

A sample of oil was obtained from each transformer and tested at Stafford Works for electrical strength and acid value in accordance with the methods described in B.S. 148 : 1951, Appendix G and H respectively. In addition an insulation resistance test was carried out in accordance with E.R.A. Technical Report E/S 4 : 1952, Appendix II, using the Forrest test cell. The results are given in Table III and indicate that no deterioration has taken place.

TABLE II.

CURRENT-TRANSFORMER DIELECTRIC LOSS ANGLE TESTS

C.T. serial number	kV R.M.S.	At Works, 22nd May 1953		At Site, 29th June 1954	
		D.L.A. (tan d)	Power factor %	D.L.A. (tan d)	Power factor %
184716	5			0·0065	0·65
	10			0·0065	0·65
	15			0·0065	0·65
	50	0·0074	0·74		
	100	0·0075	0·75		
	150	0·0077	0·77		
	185	0·0077	0·77		
	190	0·0077	0·77		
184717	5			0·0064	0·64
	10			0·0064	0·64
	15			0·0064	0·64
	50	0·0070	0·70		
	100	0·0072	0·72		
	150	0·0073	0·73		
	185	0·0074	0·74		
	190	0·0074	0·74		

TABLE III.

CURRENT-TRANSFORMER INSULATING OIL TESTS

Insulation resistance—using Forrest test cell and 'English Electric' 10 kV insulation tester

C.T. serial number	Oil temperature	Voltage	Current after 1 minute	Insulation resistance
184716	18 C	5 kV	0·16 μA	31,300 megohms
184717	18 C	5 kV	0·16 μA	31,300 ,,

NOTE : At 18 C oil is classified as 'good' if the resistance is greater than 13,000 megohms.

Electric strength—using B.S. test cell with 4 mm gap.

Serial No. 184716 : 30 kV for one minute withstand followed by 40 kV for one minute withstand. Then voltage raised until at 70 kV flashover occurred over the outside of the test cell. No breakdown between spheres.

Serial No. 184717 : as for serial No. 184716, except that flashover occurred at 68 kV.

Acid value

Serial No. 184716—0·016 mg. KOH/g of oil.
,, ,, 184717—0·018 ,, ,,

Note: B. S. Specification limit for new oil is 0.05 mg. KOH g of oil.

Conclusion

The experience described in this article is extremely valuable in providing practical proof that the design, quality of materials, workmanship, methods of production and testing in both works and laboratory that go into the manufacture of British switchgear is a guarantee of satisfactory performance under service conditions. Furthermore, although system voltages above 200 kV have been introduced in Great Britain later than in some other parts of the world, this high degree of performance has been achieved in this range.

To meet requirements for even higher ratings extending to 400 kV and possibly 500 kV, and 25,000 MVA in breaking capacity, development has been and is proceeding on the lines of the foregoing description, showing that British manufacturers can provide switchgear for any system requirements which are likely to occur in any part of the world in the foreseeable future.

Acknowledgments

Thanks are expressed to the Central Electricity Authority, to the Yorkshire and East Midlands Divisions of the Authority, and to Messrs. Merz and McLellan, for their willing co-operation concerning this installation.

The Napier 10-Channel Electronic Recorder

IN CONNECTION with certain investigations into the functioning of complex fuel metering devices, the Flight Development Establishment of D. Napier and Son Limited required a relatively inexpensive 10-channel electronic recorder. At the time (early in 1952), the specification could not be met by any commercial recorder that was readily available. The urgency with which the apparatus was required left no alternative but to design and build the recorder at the Establishment's Instrumentation Department.

As there was no time to embark on a comprehensive development programme, it was necessary for the design, development and construction to proceed together. Consequently, although several novel features were introduced, established techniques were used wherever possible and an instrument was produced which has been highly satisfactory in practice.

In general, multi-channel electronic recorders have proved themselves to be important pieces of laboratory equipment, fulfilling, as they do, the need to record many variables simultaneously, often over very short time intervals.

A typical apparatus includes a series of pick-ups, one to each channel, which transform the physical effects to be measured (i.e. strain, pressure, flow rate, etc.) into electrical signals. These signals, in turn, vary the input voltage of an amplifier, the output being displayed on a cathode-ray tube as a spot of light whose height varies above or below a predetermined datum and is directly proportional to the magnitude of the effect being measured. A permanent record of the test results is made by photographing the cathode-ray tube display on to sensitised paper moving horizontally, a line being produced from whose ordinates the magnitude of the effect can be measured with reference to a previously calibrated scale. To provide a time base for each record, a separate signal at a set frequency is displayed by an additional cathode-ray tube, and recorded along one edge of the paper.

It is in presenting the display that difficulties arise with multi-channel recording. Usually, a cathode-ray tube adjustable for focus, brilliance and beam shift, would be used for each channel. Thus, for 10-channel recording, there would be at least thirty controls to adjust for these functions

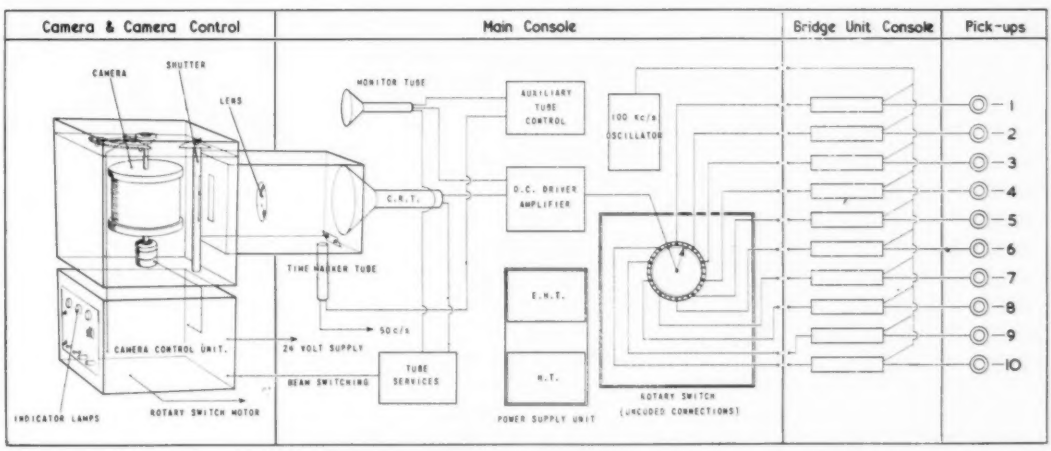


Fig. 1.—Diagrammatic layout of 10-channel recorder

alone. A more intractable difficulty arises when photographing such a multiple display. It is essential that the photographed traces be strictly comparable with each other, and this requires a complicated optical system for the camera. Also, as small cathode-ray tubes are normally used, it is an advantage if the vertical scales of the traces are optically magnified. This results in the use of very wide sensitised paper unless a transparent negative is used and the image enlarged on printing.

In the Napier 10-channel recorder a successful effort has been made to overcome the above difficulties. Only one cathode-ray tube is used, a motor-driven rotary switch being employed to switch in each channel in turn. The resulting photographic traces consist, therefore, of a series of dots instead of hard lines. In addition, the trace from each channel can be identified by a coding system applied to the spacing of the dots.

A schematic diagram showing the layout of the main components of the apparatus is illustrated in Fig. 1.

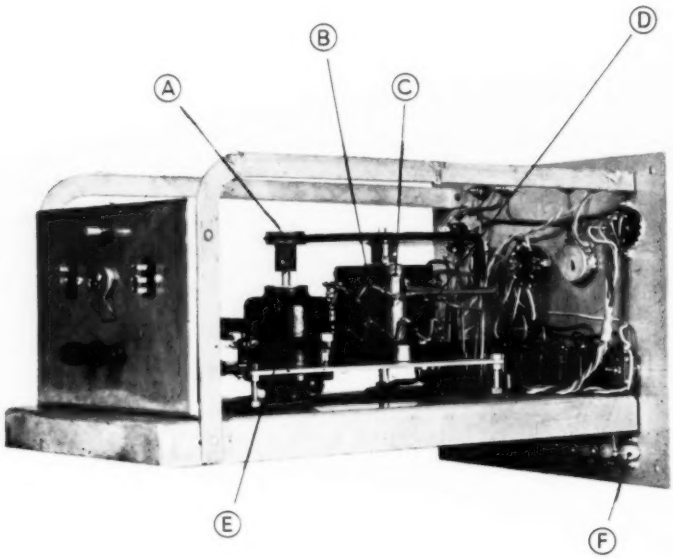
General Description

The pick-ups are designed and supplied by Southern Instruments Limited. These are essentially small variable capacitors functioning as pressure gauges, the applied pressure altering the capacitance by deflecting an insulated metal diaphragm, the pressure/capacity relationship being approximately linear.

To convert the capacity changes of the pick-ups into voltage variations, impedance bridge circuits are used, in each of which the pick-ups form one arm, all the bridges being energised in common by a 100 Kc/s oscillator. In action, the change in capacitance of a pick-up unbalances the appropriate bridge which produces, after rectification, a D.C. signal for the main amplifier and cathode-ray tube. Thus each 'bridge unit' comprises a sensitive 100 Kc/s bridge, an amplifier, and a system of rectification which provides a D.C. output of reversible polarity.

Balancing of each bridge is carried out using a 'magic eye' to indicate the null point. If perfect balance is achieved, all ten traces on the photographic record will have a common origin. However, by introducing a deliberate out-of-balance increment, each trace can be set to a different origin.

From the bridge units, the D.C. signals are fed to the input panel in the main console, the rotary switch being located in this unit as illustrated in Fig. 2. The function of the rotary switch is, first, to 'scan' the ten pick-up channels approximately sixteen times a second, so that the signal from only one channel is displayed on the cathode ray tube at a given instant. Its second function is to 'code' each signal for easy recognition on the sensitised



A. Reduction Drive
B. Channel Selector (Coded)
C. 30-Pole Rotary Switch
D. Beam Switch
E. 24 volt D.C. Driving Motor
F. Input Sockets

Fig. 2.—Rotary switch mounted on input chassis

paper. The circuit is arranged to blank out the beam between channels, thus eliminating any spurious signals caused through the function of switching. This may be regarded as a purely precautionary measure, as in practice the switch makes and breaks very cleanly.

A plastic cylinder forms the switch body which contains two sets of thirty contacts flush with the inner surface and equally spaced around the circumference. The lower set of contacts is the beam switching section, its function being to switch on the cathode-ray tube beam just after the channel has been selected, and to switch it off just before the channel is left. Channel selection and coding is carried out by the upper set of contacts, each of the ten channels being connected to one or more of the thirty contacts in this section. If, for example, Channel No. 1 is connected to the 1st, 3rd and 5th contacts, and Channel No. 2 is connected to the 2nd, 4th, 6th and 9th contacts, then for every revolution of the switching arm No. 1 channel will be presented three times, and No. 2 four times. In addition, the repetitive pattern of the spots in each of these traces will be different, and so enable easy identification if the two photographed traces run together and then separate. By connecting each of the ten input channels much as just described, each can be identified on the record by its distinctive trace.

The revolving switching arm consists of a vertical shaft concentric with a pulley, the rim of which is driven by a D.C. motor. The wipers are arranged on the shaft like the teeth of a comb, each wiper being individually spring-loaded to ensure continuous even pressure when passing across the contacts.

In service, the design of the rotary switch has proved entirely satisfactory. The make and break characteristics are very good at all speeds up to about 1,700 r.p.m. (whereas in service the switch is normally run at only 1,000 r.p.m.), the spots on the cathode-ray tube remaining small and well defined.

The driver amplifier is of conventional design and quite small. It receives the D.C. input from the bridge units via the rotary switch and presents it to the deflector plates of the cathode-ray tube. Two extra driver amplifiers are provided in the main console and may be employed as pre-amplifiers when required, or simply as stand-by units. It is from the driver amplifier that the main amplitude and cathode-ray tube shift for all channels are controlled.

Fully amplified signals are presented on the main cathode-ray tube which is 6 inches in diameter and of the electrostatic type having a blue screen of short persistence. The blue spot produced has a high actinic value and leaves an excellent image on film or sensitised paper.

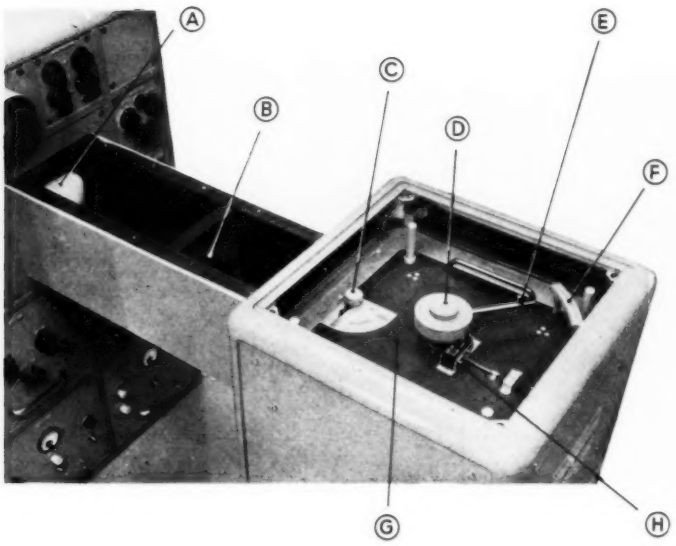
In addition to the main cathode-ray tube there is provided, for the convenience of those running the recording apparatus, a visual monitor tube showing a display identical to that on the main tube. It is smaller than the main tube, having a green screen 3 inches diameter with a vertical scale on the face to enable definite amounts of beam shift to be selected. If required, the monitor tube can be disconnected from the main driver amplifier and used to display the signal from only one channel by connecting it to the appropriate pole on the rotary switch through one of the extra driver amplifier units.

A 50 c/s timing trace is provided by a time marker tube $1\frac{1}{2}$ inches diameter and having a blue screen. This is mounted vertically at the end of the camera tunnel, the image of the beam being reflected to the camera by a mirror. The 50 c/s signal is obtained from the mains supply, shift controls being provided so that only the bottom fraction of the sine wave appears on the record as a series of vertical dashes along one edge.

The principal controls for the main cathode-ray tube and monitor tube are arranged together on the tube services panel, the auxiliary tube control panel carrying the focussing and brilliance controls for the monitor tube and time marker tube. The shift control for the time marker tube is on the input panel adjacent to the multi-point socket from which it is supplied, although once this control is set it seldom requires re-adjustment.

H.T. supply for the various services and the E.H.T. supply for the cathode-ray tube are obtained from two adjacent chassis mounted on the bottom rack of the main console.

To photograph the main cathode-ray tube display, a camera and its controlling gear are contained in a separate housing connected to the main console



A. Main Cathode Ray Tube
B. Camera Lens
C. Camera Shutter
D. Micro-Switch Cam
E. Retractable Calibration Arm
F. Calibration Quadrant
G. Camera Drum Case
H. Micro-Switch

Fig. 3.—Arrangement of camera

by a light-tight tunnel which carries the lens. An inspection flap is fitted on top of the tunnel so that the tube display can be observed during setting-up. The general arrangement of the camera housing and lens tunnel is illustrated in Fig. 3.

Light enters the camera unit through a shutter consisting of two concentric tubes mounted vertically in the front of the unit and slotted for most of their length. To open or close the shutter, the centre tube is turned by hand to bring the slots in line. Behind the shutter is a single drum 9½ inches in diameter wrapped with sensitised paper 140 mm wide. It is driven by an A.C. gramophone motor through a system of pulleys which can be adjusted to record test runs of between five and eleven seconds duration. The drum shaft extends through the top of the unit and carries the calibrating pointer (shown retracted in Fig. 3). Fully extended it is engaged with one of the numbered grooves on the calibrating quadrant while the calibrating scale for the correspondingly numbered channel is being photographed. The whole drum unit can be removed by the lifting handles and inverted on to the four pillars, thus permitting withdrawal of the drum when changing the sensitised paper.

Mounted immediately beneath the camera is the control unit, consisting principally of a multi-bank uni-selector switch and associated relays. The purpose of the camera control unit is to combine, as far as possible, the various operational functions included in the recording procedure, and to cause them to take place automatically at the press of a button. The operating sequence of the uni-selector switch is initiated by the camera drum, whose full cycle of operations takes place in two revolutions. A simple cam at the top of the camera shaft operates a micro-switch which conveys positional information (i.e. stop and start) once in each revolution to the control unit. This, in turn, switches in the cathode-ray tube beam and the appropriate indicating lamp at the correct points in the recording cycle.

Visual indication of the different stages of the recording cycle is provided by three indicator lamps—white, green and red—mounted on the camera control panel. A duplicate set can be situated anywhere in the test house for convenience of the test operator, a connecting plug being provided on the panel.

General views of the Napier 10-Channel Electronic Recorder are shown in Figs. 4 and 5, the ten impedance bridge units being independently housed in the taller console.

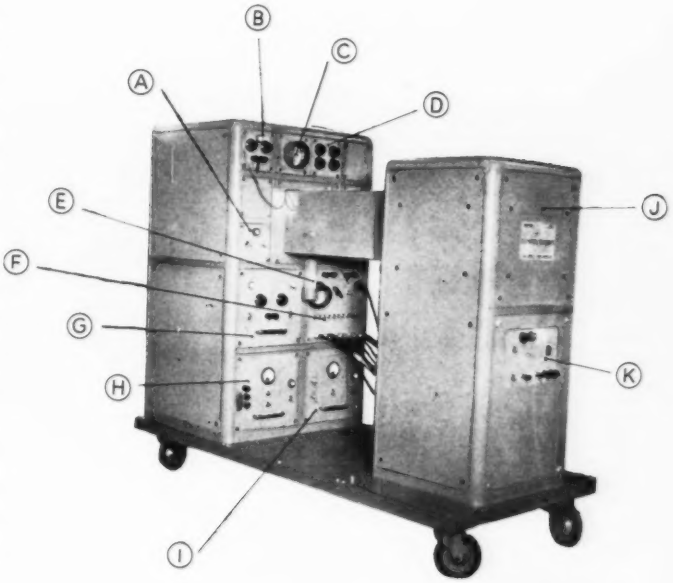
Calibration and Operation

There is a choice of three possible calibrating procedures ; whichever one is employed depends on such circumstances as the frequency of tests and the rig facilities available.

In the first method the pressure pick-up for each channel is connected to a pressure source operated

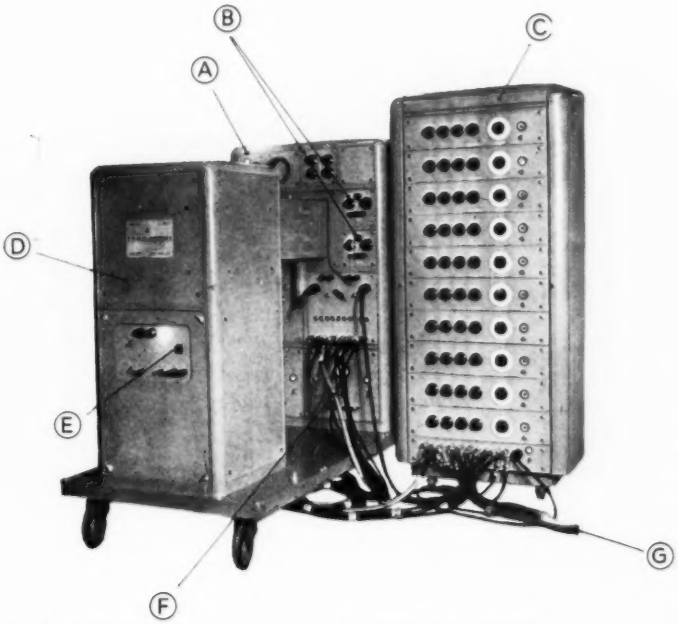
by a deadweight tester, or measured by a standard pressure gauge. The appropriate bridge unit is balanced, the null point being indicated by the magic eye. Known pressures over a predetermined range are then applied to the pick-up and the bridge is balanced after each increment, the dial readings of the calibration control being carefully noted when the null point has been achieved. The pick-up is then disconnected from the tester and the null point at zero pressure is selected on the calibration control dial.

A switch on the input panel cuts out the rotary switch and can be set to select the channel being calibrated for presentation on the cathode-ray tubes. The beam is switched on and



A. 100 Kc/s Oscillator Panel
B. Driver Amplifier Panel
C. Monitor Cathode-Ray Tube
D. Auxiliary Tube Control Panel
E. Time Marker Tube
F. Input Panel
G. Tube Services Panel
H. H.T. Power Supply Panel
I. E.H.T. Power Supply Panel
J. Camera Unit
K. Camera Control Unit Panel

Fig. 5.—Main unit



A. Main Console
B. Additional Driver Amplifiers
C. Impedance Bridge Unit Console
D. Camera Unit Console
E. Remote Indicator Lamp Plug
F. Leads from Impedance Bridge Units
G. Pick-up Leads

Fig. 4.—Main unit and impedance bridge console

the zero datum is set by operation of the shift controls. If a centre zero is selected (the scale on the monitor tube allowing any setting with some accuracy), alternate channels may be set to record above and below the line to avoid confusion with many overlapping records. This is achieved by setting a switch (provided on each bridge unit panel) which reverses the polarity of the signals.

The next stage is to transfer the calibration to the photographic record. The calibrating arm on the camera drum is extended and located in the appropriate notch of the

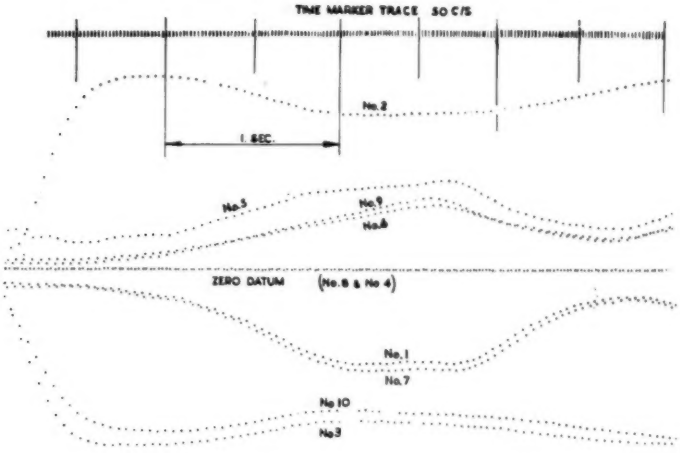
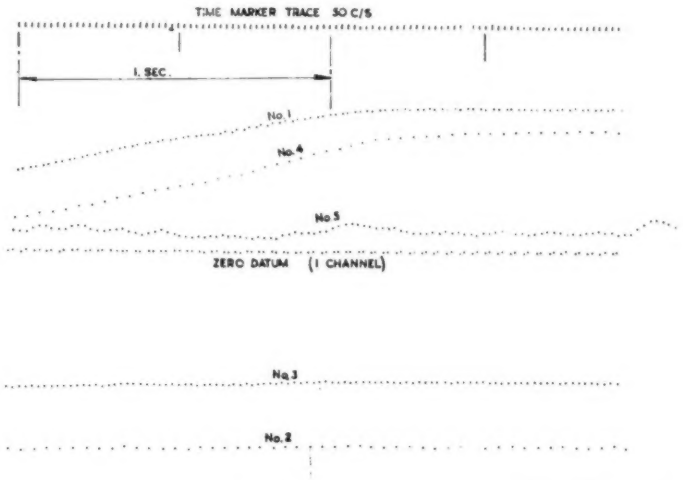


Fig. 6.—Uncoded traces (10 channels)

Fig. 7.—Coded traces (5 channels)



calibrating quadrant, after which the camera shutter is opened and the beam momentarily switched on to record the zero point. This is followed by setting the calibration control to unbalance the bridge by the amounts already noted corresponding to the set pressures. For each setting, the calibrating switch is operated, causing the spot to appear for the short length of time required to ensure that each point of the calibration scale is not over-exposed.

The usefulness of the above method is apparent when a series of similar tests is being carried out in quick succession. Time is saved after the first calibration, as the pick-ups themselves need not be re-connected to the deadweight tester, the points on the calibration scales being selected by dial adjustment only.

For single tests, a variation of the above method is to calibrate the record straight from the deadweight tester. In this case the procedure is to determine the null point on the bridge unit at zero pressure, and as each increment of pressure is applied to the pick-up, the beam is momentarily switched on and photographed.

Although low capacity co-axial input leads are used connecting the pick-ups to the bridge units, it is recognised that undesirable capacity effects can occur which unbalance the bridge units when the leads are moved after pick-up calibration for connection to the test rig. Whenever possible, therefore, accurate calibration of the record should be carried out by applying known pressures to the pick-ups *in situ* on the rig, and recording the beam variations produced.

Once the record has been calibrated, and the pick-ups are all set up in the test rig, the actual recording process is comparatively simple.

To start the automatic process, the drum must be in such a position that the calibrating arm, although retracted, is within the compass of the calibrating quadrant, thus ensuring that the micro-switch cam is correctly located. The 24-volt and mains supplies are switched on, the 'manual reset' switch on the camera control panel being operated to light the white indicator lamp. The recording sequence is now 'off' and fully set ; the display on the main cathode-ray tube and time marker tube is switched off, and under control of the camera controller.

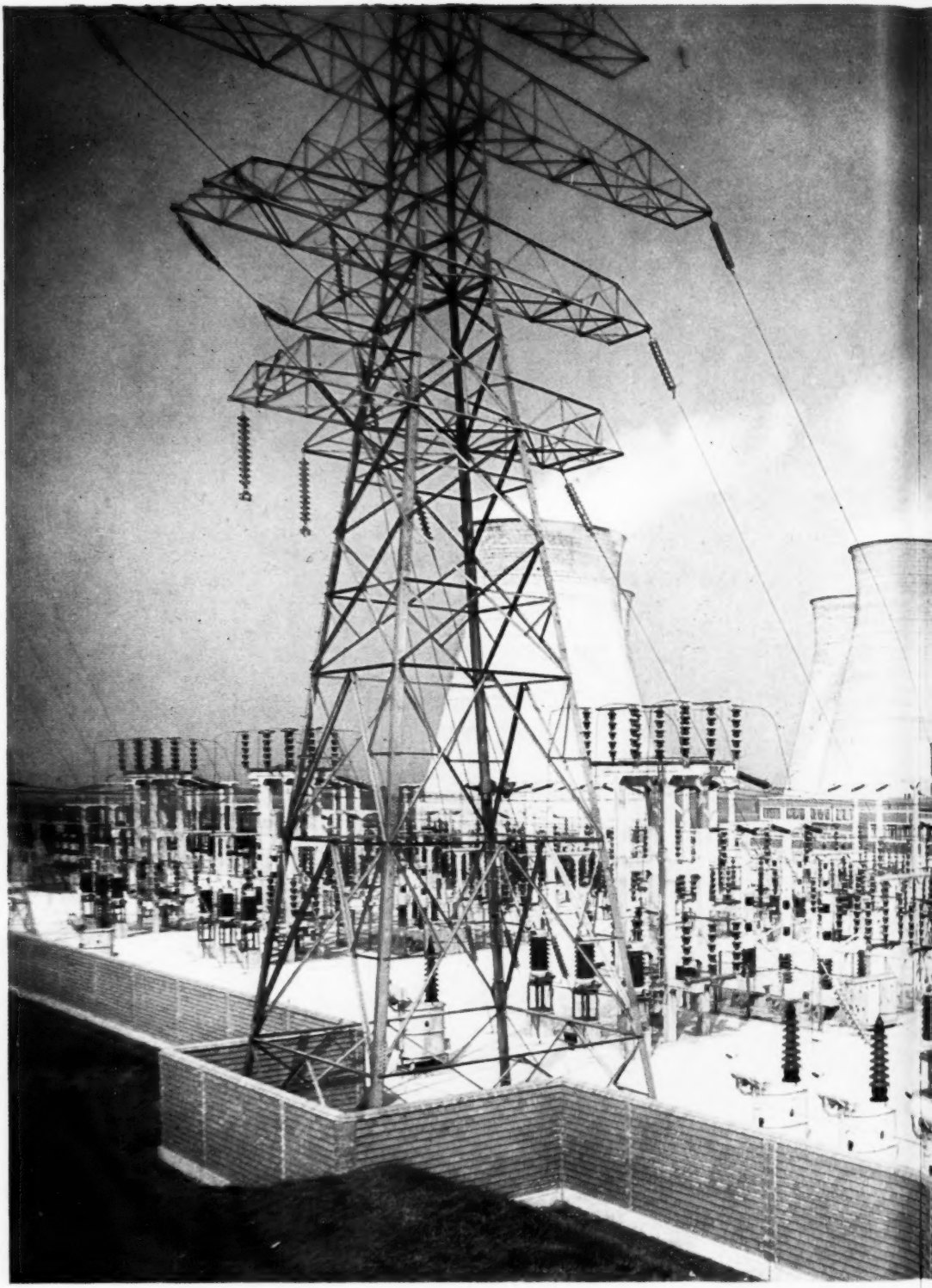
To initiate the recording cycle the shutter is opened and the 'start' button is depressed and held down until the white indicator lamp goes out, being replaced by the green. At this stage the cam-operated micro-switch has been actuated at the first 'on' position of the cam. One revolution of the camera drum is completed with the cathode-ray tube beams switched off to allow the drum to settle down to a steady speed. On completion of the first revolution, the cam operates the micro-switch at the first 'off' position but without causing any change in conditions, after which the second 'on' position is reached and the control unit switches in the beams, extinguishing the green indicator lamp and lighting the red one. During this revolution, recording takes place, ending only when the micro-switch is operated at the second 'off' position. When this is reached, the beams are switched off and the drum driving motor stops. The camera shutter may now be closed, and the drum unit removed from the recorder for the sensitised paper to be changed in a darkroom.

In the recording of transients of short duration it is common practice to ensure synchronism of the recorder with the event by arranging for the recorder to initiate the event. On the camera control panel are mounted two terminals connected to a switch which is closed automatically half a second after the cathode-ray tubes are switched on, as the camera begins its recording run. Connections from these terminals may be made to the test rig in order to initiate the test by closing a circuit.

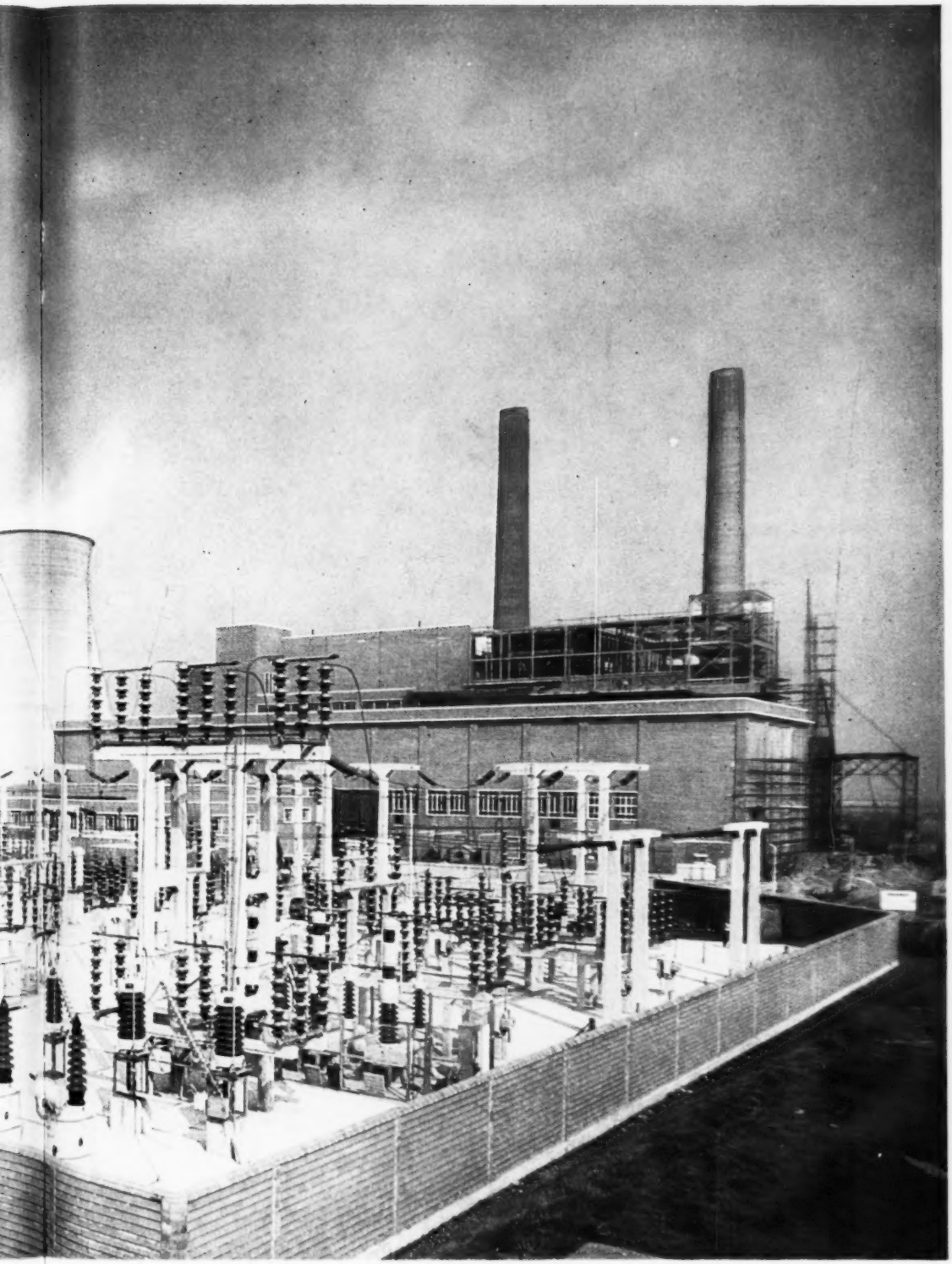
Figs. 6 and 7 are copies of sections of actual records, both being taken using an earlier type of rotary switch, this being only a 10-pole unit. The traces in Fig. 6 are uncoded, eight channels being connected to pick-ups, the remaining two channels being used to provide a datum line. The record shows quite clearly the difficulties in interpretation that may arise when uncoded traces merge and separate. Fig. 7 shows a record taken using only five channels connected to pick-ups. In this case each trace has a distinctive appearance due to coding, the zero reading from a sixth channel providing a datum line.

As designed, the recorder can be used in any application where the effects being measured can be translated into capacitive or inductive changes in the pick-ups. For strain-gauge recording the impedance bridge units cannot of course be used, as resistive changes are involved. However, by substituting suitable pre-amplifiers for the impedance bridge units, the remainder of the recorder can be used unmodified. In addition, further amplification can be achieved by introducing one or both of the extra driver amplifiers provided.

In service, the instrument has proved to be robust and relatively simple to operate. No knowledge of electronics is required by the operator, but an apparatus of this size necessarily demands his whole attention during setting-up and recording.



The 132 kV duplicate busbar switching station at the Ince Power Station of the North West, Merseyside and N
air-blast circuit-breakers of the same general design, incorporating identical interrupters, as the 275 kV



ide and North Wales Division of the Central Electricity Authority. This sub-station incorporates nineteen 2500 MVA 275 kV air-blast circuit-breaker installed at West Melton, which is the subject of the first article in this issue.

The Planetary Mill and Its Drive

By J. TUDOR JONES, Engineering Section, Metal Industries Division.

With the exception of some minor details, this article is a reproduction of the paper read by the author at the joint meeting of the Senior and Students' Sections of the South Midland Centre of the Institution of Electrical Engineers, in Birmingham, on the 7th of February, 1955.

THE PLANETARY MILL has been recently developed as an entirely new method of hot rolling metal strip. The first production unit in the world commenced rolling mild steel at the works of Ductile Steels Ltd. in Wolverhampton, England, in 1953. A second mill has since been commissioned in Canada and several more are under construction. In view of its inherent advantages the principle is likely to be used fairly extensively in the future, on alloy-steels and on some non-ferrous metals.

Certain details given in this article apply to the first mill, for which The English Electric Company was the main electrical contractor, which is designed to roll alloy-steels down to ·040 inch from slabs $1\frac{1}{2}$ to $1\frac{3}{4}$ inches thick and 15 inches wide. The general principles, however, would apply to any planetary mill.

Arrangement and Operation

The outstanding reduction in thickness, possible in only one pass, is due to the unique arrangement of the planetary rolls, indicated in Fig. 1. Two 20-inch diameter main rolls are driven at 495 r.p.m. Each main roll is surrounded by a cage of twenty-six 2-inch diameter planet rolls. The ingoing slab is forced into the gap between the planet roll cages where the main reduction in thickness takes place.

Fig. 2 shows the rolling action in greater detail. The assembly resembles two roller bearings in which the main rolls represent the inner races, and the material between the planet rolls represents the outer races. From this analogy it may be seen that as the main rolls rotate at 495 r.p.m., the cage of planet rolls rotates at about 225 r.p.m., with each planet roll revolving at 2,500 r.p.m. In this manner a planet roll from each cage rolls over the wedge-shaped end of the slab every 1/100 second, during which time the slab moves forward about ·015 inch. This results in the slab being reduced to a thickness equal to the gap separating the two cages.

The slab is pushed into the planetary roll-bite by a pair of 22-inch feed rolls, which by making a small reduction in thickness of the slab is able to overcome the opposing rolling reaction force of up to 10 tons and fix the entry speed of the mill at up to 9 f.p.m.

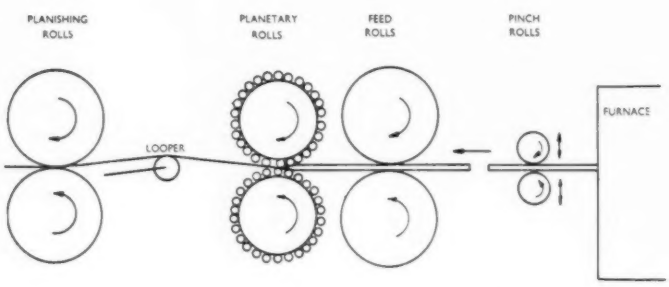


Fig. 1.—Diagrammatic arrangement of planetary mill

Fig. 3 shows a planetary mill with the main rolls withdrawn from the housing. To maintain corresponding planet rolls on the respective cages exactly opposite, the cages are coupled by bevel gears and lineshaft. Until the slab is entered, the cages are driven at the correct speed by the main motor through a clutch, which is disengaged during rolling, when the planet rolls are driven purely by friction from the main rolls.

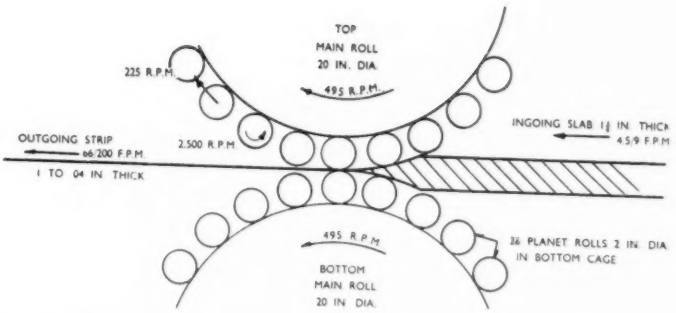


Fig. 2.—Planetary rolling action

The slabs are heated in a continuous furnace to a temperature of about 1,000°C. The furnace comprises a number of heating and soaking sections through which the slabs are passed on water-cooled rolls driven at the ingoing mill speed.

To maintain the continuity of the forward thrust, the slabs must be butted end-to-end. A set of pinch rolls between the feed rolls and the furnace runs slightly faster than the mill. When a gap occurs between two slabs, the pinch rolls are closed to engage and accelerate the following slab.

Certain slight irregularities in the surface of the strip arising from the planetary rolling action are removed by a small reduction in thickness which is made in the 18-inch 2-high planishing mill which follows the planetary rolls.

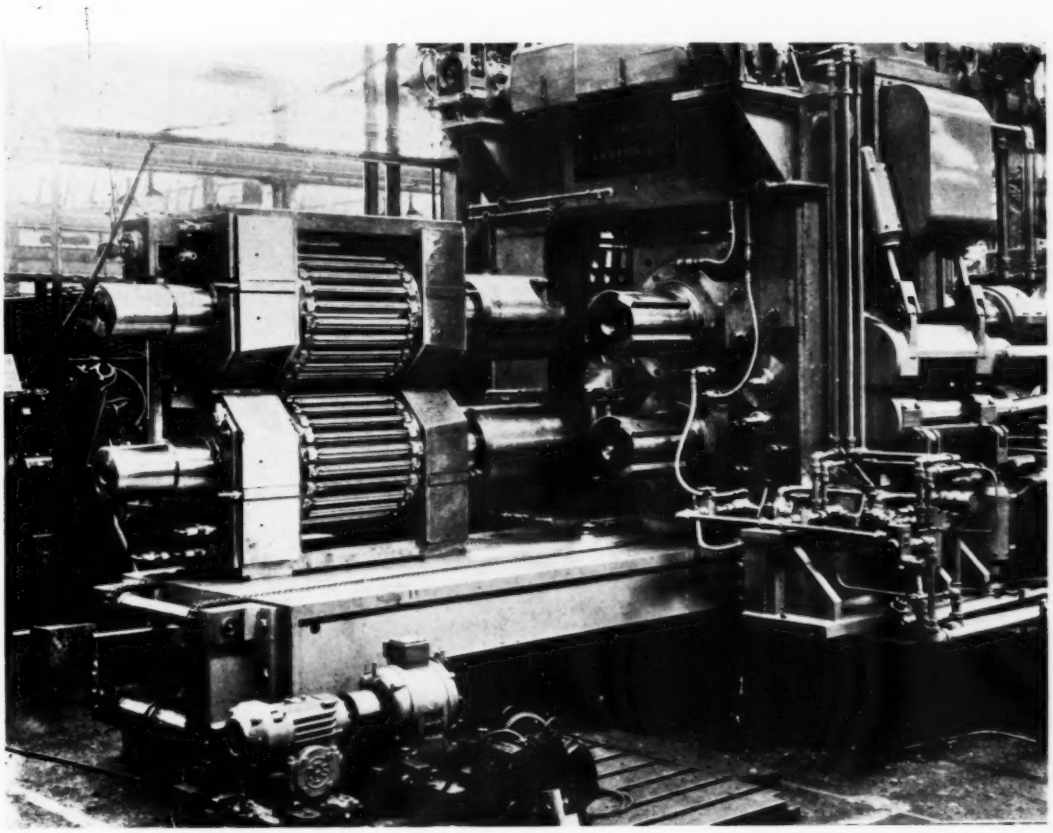


Fig. 3.—A planetary mill with the main rolls withdrawn from the housing

After passing through the planishing mill the strip cools on a 100-foot run-out table and is coiled in a 3-roll coiler.

Advantages

The main advantages of the planetary mill over the orthodox arrangement are :—

(*a*) The maximum reduction per pass of not much more than 30-40% in an orthodox mill would mean about half-a-dozen passes each on reversing roughing and intermediate mills, followed by a four or five stand tandem finishing mill. The planetary mill therefore offers much saving in plant and building size.

(*b*) To reduce heat loss during rolling, the finishing speed of an orthodox mill would be, say, 2,000 f.p.m. When an output of, say, 10 tons per hour is required, the planetary mill could roll at 200 f.p.m. The load factor of the orthodox mill would therefore be about 10% against almost 100% for the planetary mill, resulting in smaller machines, greater overall efficiency and reduced power costs for the planetary mill.

(*c*) On the planetary mill the initial slab temperature may be somewhat lower than on an orthodox mill where there is greater heat loss during rolling. The lower temperature results in less oxide scale formation and consequently gives improved quality of strip surface.

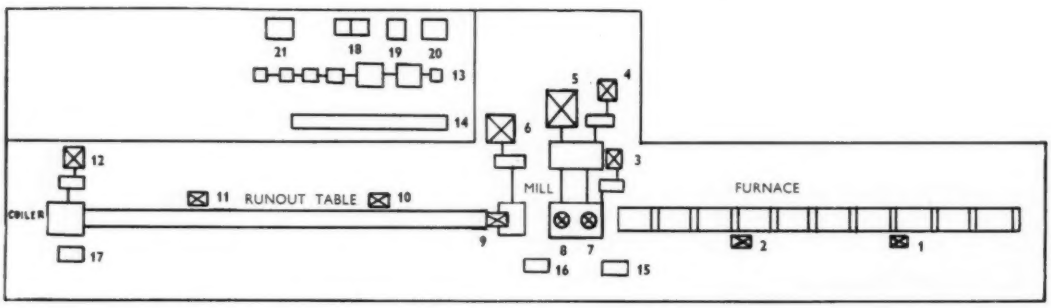
(*d*) The tail end of the strip on the final pass on an orthodox mill is somewhat cooler than the leading end due to a longer period of heat loss. As a result it may be appreciably thicker after rolling. The planetary mill's continuous action ensures an even temperature, resulting in consistent thickness, throughout the strip length.

Electrical Equipment

Careful consideration of the special rolling technique for the planetary mill was made before deciding upon the electrical equipment for the various drives. These drives are shown with the layout of the mill in Fig. 4.

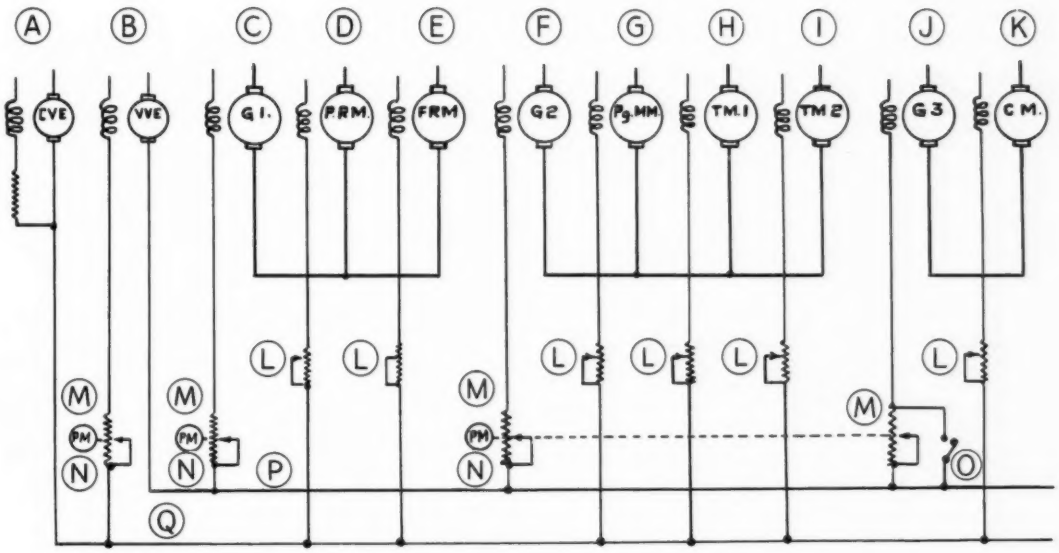
The basic requirements were as follows :—

One 900 h.p. constant-speed motor for the planetary rolls (5).



1. Furnace roll motor
2. ,, ,, ,,
3. Pinch roll motor
4. Feed roll motor
5. Planetary roll motor
6. Planishing roll motor
7. Feed roll screwdown motor
8. Planetary roll screwdown motor
9. Planishing roll screwdown motor
10. Table roll motor
11. ,, ,, ,,
12. Coiler motor
13. Motor-generator set
14. Main contactor board
15. Mill entry control desk
16. Mill exit control desk
17. Coiler control desk
18. Circuit-breakers for motor-generator set and planetary roll motor
19. Liquid starter for motor of motor-generator set
20. Liquid starter for planetary roll motor
21. Main power transformer

Fig. 4.—Layout of electrical equipment



A. Constant voltage exciter
B. Variable voltage exciter
C. Generator 1
D. Pinch roll motor
E. Feed roll motor
F. Generator 2
G. Planishing mill motor
H. Table motor 1
I. Table motor 2
J. Generator 3
K. Coiler motor
L. Trimmer rheostat
M. Motorised rheostat
N. Rheostat pilot motor
O. Contactor
P. Variable voltage exciter busbar
Q. Constant voltage exciter busbar

Fig. 5.—One-line diagram of Ward-Leonard control

Two 15 h.p. variable-speed motors for the furnace rolls (1) and (2).

Variable-speed motors of 7½ h.p. for the pinch rolls (3), 30 h.p. for the feed rolls (4), and 200 h.p. for the planishing rolls (6).

Two 5 h.p. variable-speed motors for the table rolls (10) and (11), and a 15 h.p.variable-speed motor for the coiler (12).

The planetary rolls run continuously and so a slipring induction motor was provided. This is started by means of an oil circuit-breaker and liquid starter, and to provide rapid stopping in an emergency an electro-hydraulic thrustor brake is automatically engaged.

The speed variation of the furnace rolls is provided by A.C. commutator motors having manually operated induction regulators for speed matching to the entry speed of the mill.

More accurate speed matching of the variable speed drives on the mill is obtained by the use of Ward-Leonard control, a one-line diagram of which is shown in Fig. 5.

The speed of the motors on the respective entry and exit sides of the planetary rolls must be maintained in the ratio of the reduction in gauge. Separate generators were therefore provided, one for the feed and pinch roll motors, and one for the planishing and table roll motors. A separate generator was also provided for the coiler motor to enable the speed of this to be increased by 75% as the end of the slab passes out of the mill. This speed rise allows a coil to be quickly completed

and discharged before the leading end of the next coil reaches the coiler which has by then been returned to the mill exit speed.

The fields of the three generators which have straight-line characteristics are supplied from a variable-voltage exciter so that the speeds of all sections of the mill may be varied as rolling conditions require.

A motorised rheostat gives individual adjustment of the entry section generator field, while matched voltage variation of the exit section and coiler generators is provided by coupled rheostats, also motorised, in their field circuits.

The end-of-coil acceleration of the coiler is provided by short-circuiting its generator field rheostat by means of an armature-current-controlled fluttering relay. Dynamic braking is provided for the planishing and table roll and coiler motors.

The 5 and 10 h.p. screwdown drives for the feed, planetary and planishing rolls require the greatest flexibility of operation. Space limitation on the mill headgear caused single motors to be used and provided with electro-magnetic clutches to give independent or dual screw operation. To save space each motor drives through a bevel gear, two motors being arranged vertically above the gear and the third horizontally but at right-angles to its normal position. Electro-magnetic brakes are provided for each of these drives.

To allow accurate setting of the rolls as well as fast emergency separation, the motors were designed for two-speed operation with a ratio of up to 4 : 1 by field weakening. They are supplied from a 32 kW constant-voltage generator which also supplies the fields of the other D.C. motors. Series resistance contactor starting is used with field weakening under the control of current-limiting fluttering relays.

The various generators and exciters are driven by a 365 h.p. synchronous induction motor designed to improve the full-load power factor of the complete installation to ·95 lagging.

Three control desks at the respective entry and exit sides of the mill and at the coiler have push buttons and control switches operating the remote cubicle-type contactor gear.

The supply for the main A.C. motors and for numerous pump and blower drives is 415 volts, 3 phase, obtained from a 1,250 kVA transformer stepping down from the 11 kV incoming mains.

Owing to the atmospheric conditions around the mill the various motors in its vicinity are force-ventilated by a fan and filter unit. The motor-generator set, control gear and switchgear are located in a pressurised room similarly ventilated.

Acknowledgments

In conclusion, the author expresses his thanks for permission to publish this article, to :—

Ductile Steels Ltd., who are operating the first planetary mill.

The Sendzimir Co. of America, who are responsible for the design of planetary mills.

Messrs. W. H. A. Robertson & Co., Ltd., who manufactured the first planetary mill.

Constant Frequency A.C. Electrical Systems for Aircraft

WITH PARTICULAR REFERENCE TO THE 'ENGLISH ELECTRIC' SUNDSTRAND CONSTANT SPEED DRIVE

WITH AIRCRAFT being required to fly at ever-increasing speeds and altitudes, the part played by their electrical equipment becomes more and more important.

In the past, electrical power has been provided by using direct current generators but direct current systems have severe limitations under the more exacting requirements of modern aircraft. On the other hand, constant frequency alternating current electrical systems have many advantages. These include lightness, improved overall efficiency and increased reliability, when compared with the older direct current systems.

There has, however, been a serious impediment to the development of constant frequency systems, namely, that until recently there has been no proved system for driving alternators at constant speed in such a manner that they can be connected in parallel.

Recently an agreement was reached between The English Electric Company Limited and The Sundstrand Machine Tool Company of America under the terms of which the former company manufactures the Sundstrand Constant Speed Drive under licence in Great Britain. Thus for the first time a comprehensive alternating current system is available to British aircraft designers.

The Sundstrand drive forms a link between the aircraft's engines which, of course, are the basic source of power, and the delicate electrical equipment, including radar, which relies on a constant frequency alternating current. Naturally the speed of the aeroplane's engines varies over a wide range, but the Sundstrand drive maintains a constant speed for the alternators and hence supplies constant frequency alternating current.

On a multi-engined aircraft a Sundstrand drive operates from each engine. This ensures that in the event of an engine failure, the electrical load is instantly taken up by the drive from the other engine or engines.

At a time when electrical power is playing a growing part in aviation the 'English Electric' Sundstrand drive will, in conjunction with other advanced electrical equipment developed by The English Electric Company, contribute to the efficiency and safety of future aircraft by saving weight and space and by giving a more reliable power supply to such essential equipment as navigational aids, radar and power controls.

I. ELECTRICAL SYSTEMS

Advantages of A.C. Systems

The advantages of constant frequency A.C. electrical systems over D.C. systems in aircraft have long been appreciated. Recent trends in design, and more arduous operating conditions, have accentuated these advantages listed below.

1. The brushwear problem at high altitudes is largely overcome.
2. Due mainly to the elimination of invertors and the fact that A.C. motors are inherently lighter than D.C. machines, the weight of a complete A.C. electrical system can be several hundred pounds less than that of an equivalent D.C. system.
3. The alternator is designed for optimum operation at one speed only whereas the size and weight of a wide speed-range machine are governed by maintaining the full rated output at the lower speed limit.

4. 3-phase induction motors are simple in construction and are lighter and smaller than D.C. machines.

5. Most of the A.C. loads can be supplied directly from the busbars.

6. The problem of interrupting heavy currents (e.g. under fault conditions) is alleviated considerably by the use of A.C., and A.C. circuit-breakers are much smaller than their D.C. counterparts for equivalent duty.

7. The supply voltage can be readily changed to any required value without recourse to rotating machines.

Method of Obtaining Constant Frequency

There are various possible methods of driving alternators at constant speed, and Table I indicates the relative merits of these according to a recent appreciation based on the study of constant frequency applied to various designs of multi-engined aircraft (using either turbo-jet or turbo-propeller engines). In piston engined aircraft, of

TABLE I

METHODS OF DRIVING ALTERNATORS AT CONSTANT SPEED, AND THEIR RELATIVE MERITS

Aspect	Systems using 'shaft' power extracted from the main propulsion engines (i.e. infinitely variable ratio drives)			Systems employing separate prime movers for the alternator but associated with the propulsion engines		Systems completely independent of propulsion engines
	Variable ratio hydraulic pump and motor drives	Hydraulic drive of the 'differential' type (e.g. Sundstrand)	Variable ratio mechanical (friction) drives	Air-turbine drives, fed by air bled from the propulsion engine compressors	Gas-turbine drives, using air bled from the propulsion engine compressors	Auxiliary power unit, of the gas turbine types
Reliability (based on practical experience to date)	Good, but not in general service	In squadron service in U.S.A. 850 hours overhaul period established	No experience for this duty	Little experience	No experience	Little experience (no experience of parallel operation)
Installed weight (in ascending order of weight)	3	1 (Assuming full power is required at high altitude)	6 (More competitive in very high altitude applications)	2 (Assuming full power is required at high altitude)	5	4 (More favourable in low altitude applications)
Efficiency (in ascending order of fuel expenditure per kWh generated)	4 Not high, due to hydraulic losses	2 High, due to differential mode of operation thus reducing power handled by oil to minimum	1 Very high	3 Low when used with contemporary designs of turbine engines	5 Low under most operating conditions	6 Low due to small size of unit
Other remarks	Flexible in installation	Compact installation particularly if designed as integral part of engine or gearbox. Frequency control and load sharing good	Relatively unknown art for highly rated applications	Control equipment complicated. Flexible in installation	Control very difficult. Installation is complicated (exhaust ducts etc.)	Difficult installation. High efficiency and low weight (small number of large units) not compatible with good reliability (large number of small units)

course, the choice of system is limited to shaft power extraction or auxiliary power unit.

In a number of investigations, hydraulic drives (differential type) have been found to be very competitive in installed weight with air turbine drives, and each application has to be given separate consideration to arrive at the lightest system. Particularly in long range aircraft, however, the higher overall efficiency of the hydraulic drive system (resulting in lower fuel expenditure for electrical power) gives this system a clear advantage over others.

A further advantage in extracting power from the propulsion engine shaft is that this has little effect on engine performance and control. There is a danger of mismatching the turbine and compressor characteristics when varying quantities of air are bled from the main engines, and the engine control system has to be arranged to compensate for any changes in the conditions if the engines are to be run at maximum permissible turbine temperatures for minimum fuel consumption.

The English Electric Company has selected the variable ratio hydraulic drive, used differentially, as being the most practicable and attractive, and a typical constant frequency system as developed by this company, using Sundstrand type drives as the means of deriving constant speed, is now described. The frequency adopted is 400 cycles/second, this being the accepted standard for aircraft A.C. supplies. The system is 200 volts 3 phase, and the frequency is controlled to $\pm$ 1% under all conditions of load and input speed.

Main Components of System

The essential equipment associated with each alternator of a multi-alternator system may be itemised as follows. Fig. 1 shows the arrangement of these components in block diagram form.

1. Constant speed drive.
2. Control unit for (1), to achieve 'real' load sharing between parallel connected alternators and precise frequency control.
3. Alternator.
4. Voltage regulator and 'reactive' load sharing control.
5. Alternator control panel, to provide adequate fault protection, etc.
6. Main circuit-breaker.
7. Synchronising unit.
8. Current transformers for real and reactive load sharing and protective devices.

Additional equipment may be required, such as transformer-rectifier units to provide a 28-volt D.C. supply for low voltage services such as lighting, control circuits, small actuators, etc.

Constant Speed Drive

Each alternator is driven from a main engine through its own constant speed drive. An alternator speed of 6,000 r.p.m. has been selected mainly on the basis of maximum reliability and short-circuit characteristic.

The 'English Electric' Sundstrand drive comprises a variable stroke pump and a fixed stroke motor combined in one cylinder unit and arranged to operate in a differential manner so that only the power represented by the difference in input and output speeds is handled by the pump and motor

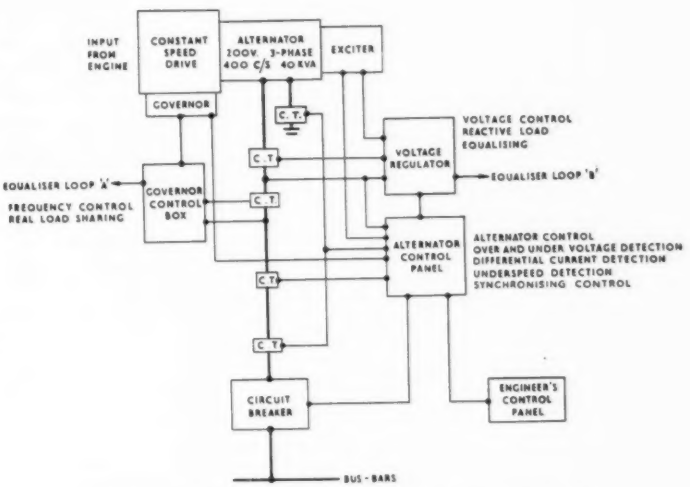


Fig. 1.—Essential components for each alternator in a multi-alternator constant frequency A.C. system

thereby reducing to a minimum the hydraulic losses and wear on the hydraulic components.

The type of drive initially produced by The English Electric Company transmits 50 h.p. continuously over an input speed range of 3,000 to 8,100 r.p.m. ; other types will follow.

Governor Control Units

The governor control circuits have two functions: to keep the alternator frequency constant and to equalise real load distribution between machines operating in parallel. If, owing to a change in engine speed or alternator loading, the frequency tends to drift from the correct value, a frequency discriminator circuit develops a rectified D.C. signal proportional to the deviation and of appropriate polarity depending on whether the frequency is tending to increase or decrease. The signal is taken to a magnetic amplifier which produces an equivalent A.C. signal which is fed to one winding of the two-phase governor control motor, the other phase being supplied with a fixed phase voltage. The control signal leads or lags this voltage by 90° and so causes the motor to rotate and adjust the governor control spring setting to correct the frequency deviation.

If one of a number of alternators operating in parallel tends to lose speed it will shed some of its real load, and as will be explained later, a current transformer is used to make this effect produce a signal in the drive control unit which will cause the governor drive motor to adjust the drive output speed so that the alternator will take up its share of the load.

Alternator

The alternator is of the separately excited type with its exciter built in as an integral part of the machine. The general design is similar to one on which several thousands of hours of operational service have been accumulated. The exciter is supported between the main bearings of the alternator, resulting in a compact complete assembly, and the characteristics of the alternator-exciter combination are such that a high short-circuit current is available for fault clearing. A further advantage of the separate exciter is the fact that it is immune from the effects of heavy overload or short-circuit, and it is so designed that there is no danger of its field becoming demagnetised or reversed.

Special consideration is given in the electrical design to limit harmonic content to a minimum and provide a wave-form which is satisfactory for all aircraft applications.

Full use is made of the active material, and to enable the machine to operate at high temperature, glass insulation is used and the windings are impregnated with silicone varnish. Iron losses are kept to a minimum by the use of high grade low loss core plate steel.

Voltage Regulator

This may be the conventional carbon pile type regulator in which the average of the three alternator phase voltages is rectified and taken to the regulator control coil. If the voltage tends to move from the correct value, the action of the control coil adjusts the resistance of the exciter field circuit so that the deviation is corrected. The carbon pile type regulator has limitations which have led to the development of the magnetic amplifier type. In this the exciter field is connected to the output of the amplifier, the control winding of which receives a D.C. signal proportional to the alternator output.

If the voltage generated by one of a number of alternators tends to fall, the other machines will take up more of the reactive load of the system. A current transformer and a ' mutual reactor ' (a transformer requiring a large magnetising current owing to an air-gap in the magnetic circuit) are used to cause the voltage regulator of the low voltage machine to increase the excitation and so correct the deviation. The operation of the associated circuit is explained later.

Alternator Control Panel

The functions of the control panel are to ensure that an alternator cannot be connected to the line if its frequency, voltage or phase rotation are incorrect, or if there is a fault on the machine, and to disconnect the machine if any of these conditions occur whilst it is running. The control panel incorporates devices which protect against the following faults:—

1. Line to line or line to neutral (earth) fault up to the alternator circuit-breaker.

2. Undervoltage or overvoltage.

3. Wrong phase sequence : this is a function covered by the undervoltage unit and is a safeguard against incorrect installation.

4. Underspeed.

Overspeed protection is arranged mechanically at the constant-speed drive.

Main Circuit-breaker

Each alternator is connected to its busbar by means of a circuit-breaker, and the type used is illustrated in Fig. 5. This unit is electrically closed and tripped, and employs double-break sintered contacts. It is rated at 120 amperes, with an interrupting capacity of up to 4,000 amperes at 60,000 ft altitude. The 'closing' coil is automatically disconnected from its supply when the closing operation is complete, and the main contacts are held closed by a mechanical latch which can be released by the 'opening' solenoid. Auxiliary contacts are provided for interlocking and indicating purposes.

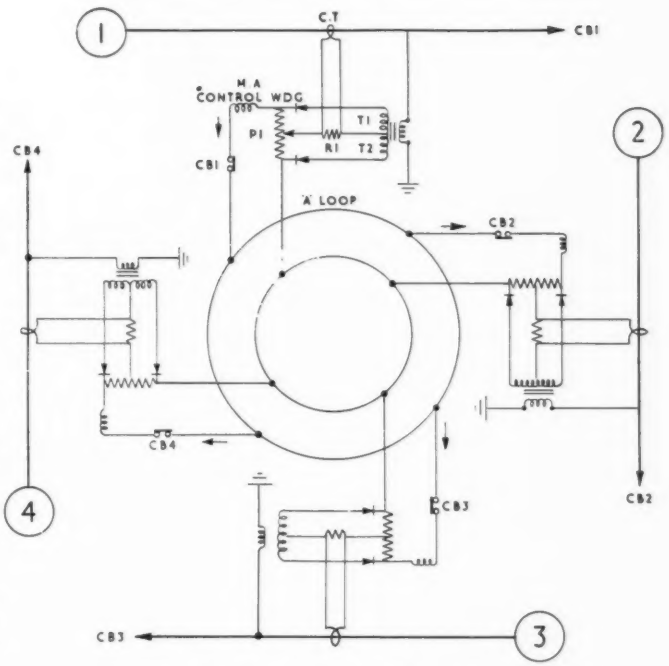


Fig. 2.—Principle of operation of real load sharing circuits

Principles of Operation

Real Load Sharing (Fig. 2)

This figure shows an installation of four alternators. Each single-phase input transformer to the circuit has two secondary windings T1 and T2 so connected that when no voltage is produced by the current transformer across resistor R1 there is no D.C. voltage across potential divider P1. Under balanced loading conditions the 'in phase' or power component of the voltages appearing across the R1 resistors are equal, each arithmetically adds to and subtracts from the respective T1 and T2 outputs thus causing the same potential difference across the P1 potential dividers. Therefore no current flows in the magnetic amplifier control windings and equaliser loop A.

If, however, No. 1 machine tends to reduce its speed, it begins to shed real load which must be taken up by the other machines. The voltage across the R1 resistor falls by an amount proportional to the reduction in load. The voltage across the other R1 resistors increases by one third this value (with four machines on line). Hence current flows from P1 on the three machines, out of the respective magnetic amplifier control windings and equaliser loop A and into the control winding of No. 1, so biasing the drive governor to tend to increase the speed. At the same time the other machines lose speed momentarily, thus restoring balance. The system frequency does not actually change during this process, being held constant by the frequency discriminator circuits. The interlocks in the connection to loop A disconnect a machine from the load-sharing circuit when the circuit-breaker opens.

Since only the 'in phase' component of the voltage appearing at R1 is effective, unbalance of reactive currents is not detected in this circuit.

Reactive Load Sharing (Fig. 3)

Under balanced reactive load conditions the

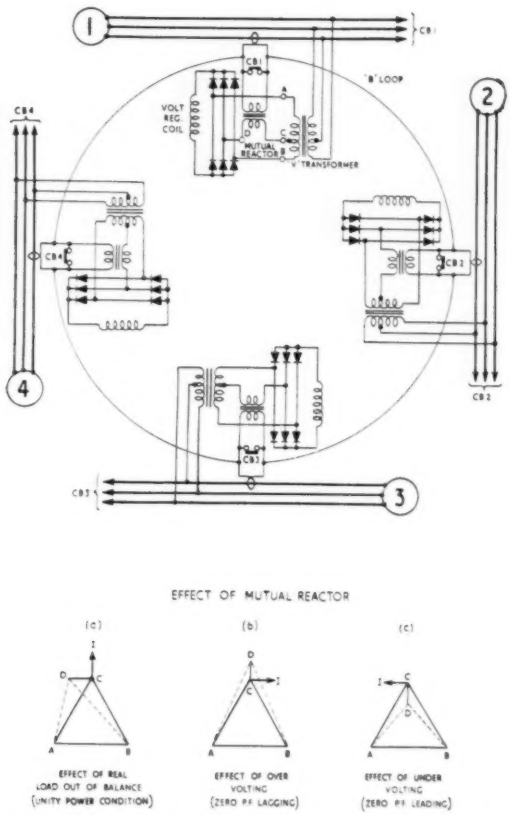


Fig. 3.—Principle of operation of reactive load sharing circuits

output of each open delta or 'V' transformer is taken directly to the rectifier supplying the voltage regulator control coil. The current in the current transformer secondaries circulates round the equaliser B loop alone.

If the voltage of one machine begins to increase, that machine takes up more than its share of the reactive load, the other machines each losing one-third of this amount. The secondary current of the overvolting machine current-transformer increases correspondingly but, as the current in loop B can only have one value, a current circulates in the mutual reactor secondary, causing a voltage to be injected into the supply to the rectifier such as to increase the average input and thus the D.C. output voltage. The regulator senses overvoltage and operates to reduce alternator excitation. At the same time the voltage of the other machines tends to rise, since the respective mutual reactor signals reduce the signals to the regulator coils. The 90° phase shift of mutual reactor secondary voltage relative to its primary current ensures that changes in resistive or real load have little effect on the signal to the voltage regulator coil. On the vector diagrams the voltages A B D are those taken to the rectifier, and the D.C. voltage depends upon the average of these.

Fault Protection

Overvoltage and Undervoltage Units

These devices protect the system from the overheating effects of the large circulating reactive currents resulting from a machine developing under- or over-excitation. The units must be selective, only removing the faulty machine from the system. This is effected by the current transformer—mutual reactor circuit, whereby if the voltage of one machine falls to 180 V on a four-machine system, the busbar voltage falls to $\frac{1}{4}$ $(3 \times 200 + 180) = 195$ V. The mutual reactor must inject a signal which will produce an average line voltage of 180 V applied to the undervoltage and overvoltage units.

It can be shown that the bias voltage required is 27 V. At the same time the sound machines are biased by a signal of $27/3 = 9$ V in the opposite sense, and the average voltage sensed by their detecting units can be shown to be 200 V even though the system voltage is at 195 V. A similar argument can be applied to the case of the overvolting machine ; with this generating 220 V, the busbar voltage becomes 205 V, the faulty machine detector senses 220 V and the others 200 V.

The undervoltage and overvoltage units are set to trip when the machine voltage exceeds the range 180-220 V, but time delays are introduced to ensure that load surges do not cause nuisance tripping.

Line-Line and Line-Earth Faults

The Merz-Price differential current protection scheme is used. The neutral lead of each of the alternator phases is brought out and passed through a ring-type current transformer. Another transformer is placed over the outgoing phase lead,

the two secondaries being connected together and to the coil of a small A.C. relay. Under normal conditions the two primary currents are equal in magnitude but opposite in phase and no current flows in the relay coil. If a fault occurs on the line between the two transformers the two primary currents will become unbalanced. When the out of balance reaches 40% of normal full load value the relay closes and removes the faulty machine from the busbar.

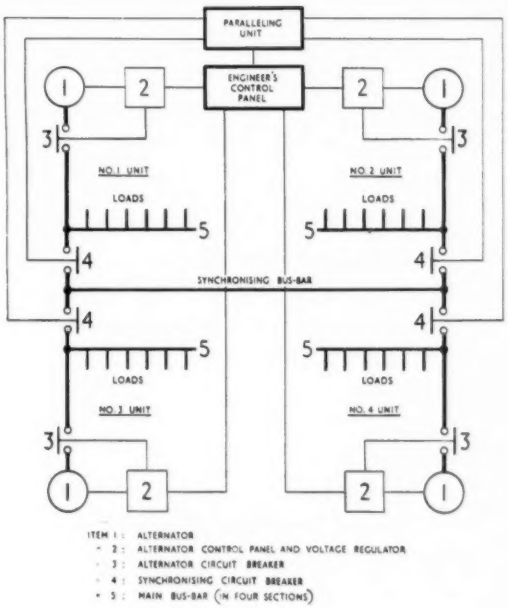


Fig. 4.—Typical system layout showing busbars and feeder arrangements

System Layout

Fig. 4 shows a typical feeder arrangement of a four-alternator system in which the main busbars are split into four sections. Normally the system operates with all the circuit-breakers closed, but in the event of a major fault on any section the appropriate synchronising breaker can be opened thus leaving three-quarters of the main busbars alive. To take full advantage of this layout the essential services can be distributed between the four sections.

Fig. 5.—'English Electric' Type 681 circuit-breaker with 4,000 amperes breaking capacity

Associated Equipment

A range of A.C. utilisation equipment is being developed to enable full advantage to be taken of the reliability and weight-saving offered by A.C. systems. This includes motors, actuators and transformers of various ratings.

The motors range from 25 watts to 5 h.p. output (or larger for particular duties), and two examples with 3-inch and 1½-inch diameters respectively are shown in Fig. 6. These are both 4 pole-designs (synchronous speed 12,000 r.p.m.) and are rated at 1·6 h.p. and 50 watts, weighing approximately 8½ lb and 1 lb respectively. They are of totally enclosed construction using surface cooling derived from a centrifugal fan mounted externally on the end of the motor.

Some 'English Electric' transformers are illustrated in Fig. 7. These employ high-efficiency rolled up 'E' Core and the larger units are designed for blast cooling for minimum weight. Transformers are used to obtain various supplies to suit particular equipment, i.e. radio and radar.

Even a so-called 'all A.C.' aircraft will always

Fig. 6.—Two 'English Electric' aircraft-type A.C. motors

carry a certain amount of low voltage D.C. equipment, and a convenient way of deriving the power for the low voltage system is the use of transformer-rectifier units. These are usually quite small, with ratings of the order of 3 kW.

Trend and Future Development

The principles underlying the constant frequency A.C. system and its advantages on certain types of aircraft are now firmly established.

Considerable effort is now being applied to the reduction in size and weight of alternators, and to this end developments are in progress to increase both their operating speed and maximum working temperatures.

The 'English Electric' Sundstrand drive, based on a proved system with tens of thousands of hours flying experience, offers an attractive solution to an old problem and is expected to find numerous applications in British aircraft.

II. THE 'ENGLISH ELECTRIC' SUNDSTRAND CONSTANT SPEED DRIVE

The advantages of constant frequency A.C. systems over D.C. systems have been explained in Part I. Of several possible methods of driving alternators at constant speed, The English Electric Company has selected the variable ratio hydro-mechanical drive as being the most practicable system. A unit is interposed between each main propulsion engine and its alternator, accepting variable speed shaft power from the engine and driving the alternator at constant speed.

In order to take full advantage of the progress already made in the development of this type of drive by the Sundstrand Machine Tool Company of America, the agreement previously mentioned was reached to manufacture in Great Britain units to Sundstrand design of a type of drive on which considerable experience has been built up in the U.S.A.

As mentioned in Part I, basically the Sundstrand drive is a positive displacement hydraulic transmission comprising a variable stroke pump and a fixed stroke motor combined in one cylinder assembly and arranged in such a way that only the power represented by the difference in input and output speeds is handled by the pump and motor.

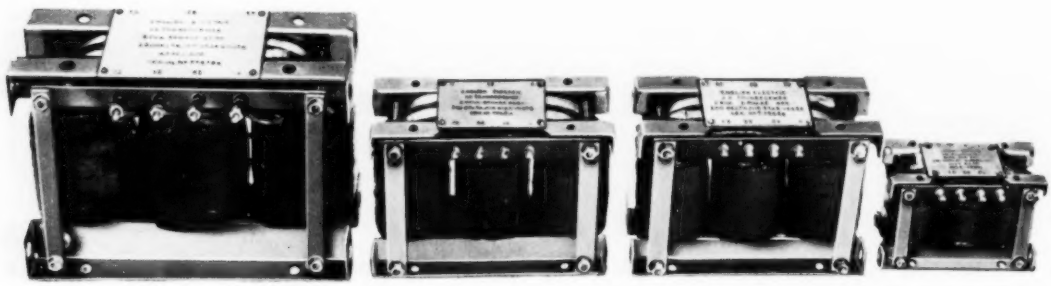


Fig. 7.—Some 'English Electric' 3-phase 'E' Core transformers for aircraft use

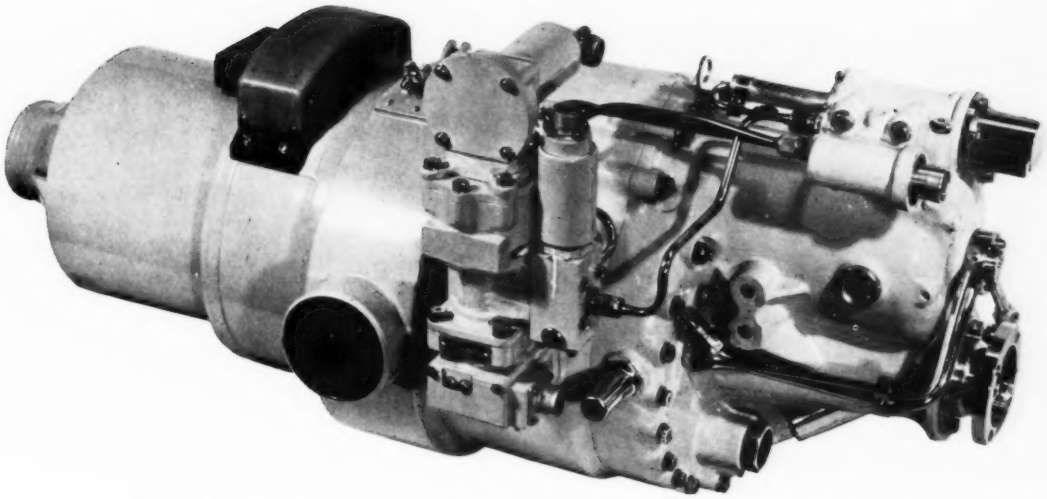


Fig. 8 – 40 kVA Package type 'English Electric' Sundstrand drive, with alternator

Several types have been developed and Fig. 8 shows a 40 kVA unit of a type known as the 'Package Drive' directly coupled to an 'English Electric' alternator. It is a similar type of drive to this that is being produced initially in Great Britain and to which the following description applies.

Principle of Operation

The 'English Electric' Sundstrand constant speed drive, shown schematically in Fig. 9 and in section in Fig. 10, comprises a variable displacement axial-piston type pump and a fixed displacement axial-piston type motor housed in a common cylinder block assembly (6 and 10) and bolted together, with the port plate (8) positioned in between to direct oil-flow between the pump and motor. Power from the aircraft engine is applied to the transmission by the input shaft and is transmitted through gears (13) to the rotating cylinder block assembly.

Initial rotation of the input shaft simultaneously starts the cylinder block assembly rotating as well as the charge and scavenge oil pumps (14 and 15). As the pump and motor are not self-priming, a gear type charge oil pump is used to deliver oil to the pump and motor assembly and the governor system. This charge oil pump supplies the inlet of the main piston pump and motor so that the pistons (1) and push rods (2) will be held in contact with the wobbler assemblies at all times, and ensures that a full charge of oil will be maintained in the high pressure hydraulic circuit.

The variable-displacement pump consists of the cylinder block assembly (6), the pump wobbler assembly (4) and the manifold assembly (3). As the charge pressure holds the pistons against the wobbler assembly, piston stroking is accomplished when the cylinder block is rotated. The displacement of the pump is regulated by the angle of the wobbler which is determined by the governor system through a hydraulic signal. The manifold assembly serves to deliver charge oil to the pump and return oil to the pressurized case.

The fixed-displacement axial-piston motor consists of the motor cylinder block assembly (10) and the motor wobbler shaft assembly (11). The motor cylinder block assembly receives high pressure oil which forces the pistons to move out against the fixed-angle wobbler, thus converting axial-piston movement into rotary motion. The motor shaft is free to rotate independently of the rotating cylinder block and hence can operate at speeds in excess of or below that of the rotating

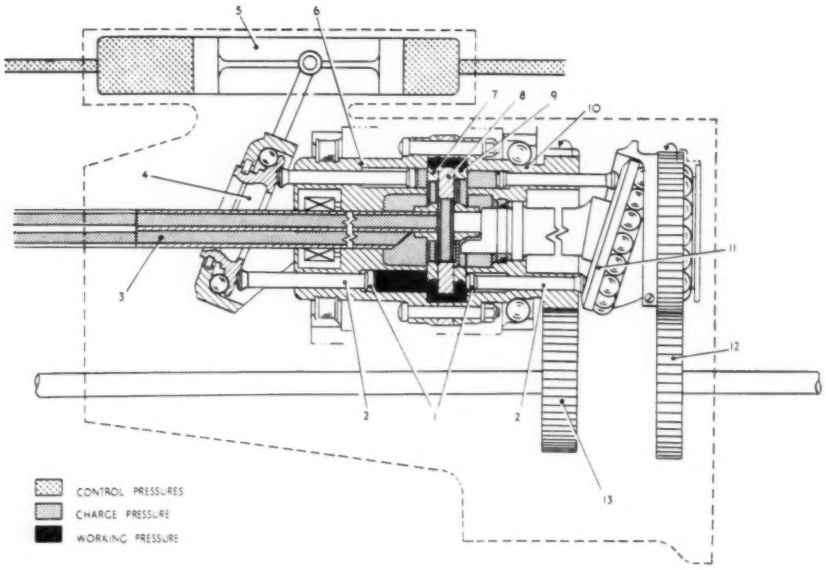


Fig. 9.—Schematic diagram of 'English Electric' Sundstrand constant speed drive

1. Pistons
2. Push rods
3. Manifold assembly
4. Pump wobbler assembly
5. Wobbler control assembly
6. Pump cylinder block
7. Pump valve plate
8. Port plate
9. Motor valve plate
10. Motor cylinder block
11. Motor (fixed angle) wobbler
12. Output gear and free-wheel clutch assembly
13. Input gear

cylinder block assembly. The offset of the motor valve plate is always in the same position with respect to the angular position of the wobbler this being such that the motor push rods are exerting a clockwise torque upon the wobbler.

With the pump wobbler in maximum overdrive (maximum positive angle), the output shaft is overspeeding the input shaft. After gear ratio corrections, this overspeed is the ratio of maximum pump displacement to the fixed displacement of the motor minus piston leakage. The wobbler remains in this maximum stroke position until output speed reaches 6,000 r.p.m.

With further increase in input speed, the normal tendency is to increase the output speed. At this point, however, the governor regulates the control piston (5) and wobbler assembly to decrease pump piston stroke. Less oil then flows from the pump to the motor and therefore the differential speed between the motor shaft and the cylinder block assembly is reduced to retain constant output speed.

When the input speed exceeds output speed the cylinder block assembly will be turning faster than the motor shaft which always operates at constant speed. Relative motion between the cylinder block and motor shaft will now be in a reverse direction since it is now necessary to subtract from input speed to maintain governed output speed. Due to the cylinder block overspeeding the motor shaft, the pump wobbler is held in an underdrive position (negative angle) which permits an oil flow from motor to pump. In effect, the pump is now motoring and the power flow in the hydraulic units is reversed.

Leakage from the cylinder block assembly and lubricating oil which drains back into the unpressurised case is picked up by a gear type scavenge oil pump (15) and returned to the external reservoir. The scavenge pump, which is attached to the same

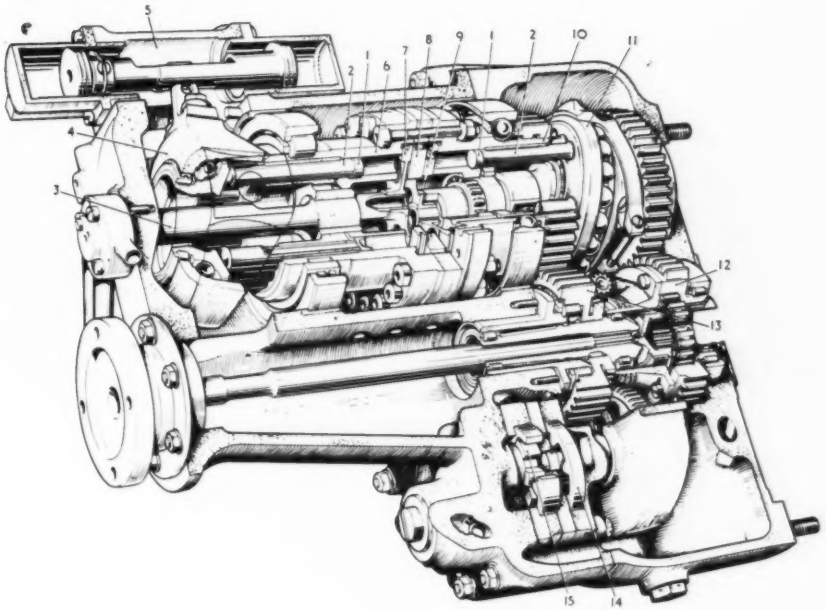


Fig. 10.—Cut-away section drawing of drive

1 Pistons
2 Push rods
3 Manifold assembly
4 Pump wobbler assembly
5 Wobbler control assembly
6 Pump cylinder block
7 Pump valve plate
8 Port plate
9 Motor valve plate
10 Motor cylinder block
11 Motor (fixed angle) wobbler
12 Output gear and free-wheel clutch assembly
13 Input gear
14 Charge pump
15 Scavenge pump

shaft as the charge oil pump (14), is large enough to ensure a dry case condition at all times.

The alternator is driven through a full complement, over-running, sprag type, one-way clutch located in the output gear and clutch assembly (12) of the transmission. This clutch is necessary to prevent power being directed through the transmission opposite to that from the main aircraft engine under conditions when the alternator is tending to act as a motor.

As the output speed has to be regulated to 6,000 r.p.m. constant, the speed signal for the governor system is taken from the output gear and clutch assembly. This signal is transmitted through the tachometer drive shaft and centrifugal switch to the governor assembly.

Hydraulic Circuit

Initial rotation of the input shaft having simultaneously started rotation of the cylinder block assembly and the charge and scavenge oil pumps, the charge pump picks up oil from the external reservoir and delivers it through the oil filter and manifold assembly to the charge oil section between the pump and motor cylinder blocks. Oil returns from the cylinder block assembly through the manifold return line to the charge relief valve. This valve maintains the charge pressure at 300 p.s.i., the excess dumping over the valve into the pressurized case. A by-pass taps off oil from the manifold return line and supplies the oil to the governor system and wobbler control pistons. The purpose of the pressurized case is to supply pressure lubrication to the various rotating parts of the transmission through properly located jet nozzles. Oil drains from the pressurized case to the unpressurized case through the lubricating oil relief valve which is adjusted to open at a pressure of 20 p.s.i.

The items required external to the drive are an

oil reservoir, an oil filter, and an oil cooler. The cooler must be of adequate capacity to deal with the heat losses of the drive as indicated in Table II.

TABLE II

HEAT LOSSES IN HYDRO-MECHANICAL CONSTANT SPEED DRIVE

Drive input speed r.p.m.	Heat rejection in B.Th.U. per hour	
	100% load	50% load
3000	19,000	10,000
4000	19,000	10,000
5000	20,000	10,500
6000	22,000	12,000
7000	26,000	15,000
8000	30,000	20,000

A particularly attractive scheme in some installations is to integrate the Sundstrand oil system with the engine oil system, using a cooler of adequate capacity to deal with the heat rejection from both the engine and the constant speed drive.

The use of a fuel-cooled oil system often enables a very useful weight reduction to be effected.

Basic Governor System

The governor system has two functions : to control drive output speed, and thereby alternator frequency, and to equalise real load among paralleled alternators. Each drive-alternator control system consists of a governor control, a precision frequency control motor, and a frequency and load controller. The arrangement and operation of these elements make it possible accurately to control pump wobbler angle through the control pistons, and hence to control output speed of the transmission. A close speed control is achieved by this means, and the frequency of the system is held within $\pm$ 1% over the range of load and input speed conditions.

The governor control is a spring-biased, flyball-operated, hydraulic control valve. Its function is to control the porting of oil under charge pressure to the overdrive and the underdrive control cylinders. A rotating sleeve in the governor control is driven from an output gear of the drive and is therefore responsive to output speed. At one end of the sleeve are two flyweights whose arms tend to move a two-land valve stem in the sleeve against the tension of two springs ; the main spring, whose tension is pre-set, and a smaller bias spring whose tension is controlled through a plunger rod by the precision frequency control motor.

Four ports connect to the valve chamber in the sleeve ; an inlet port carrying charge oil, a port which drains to the lubrication circuit, a port to the overdrive control cylinder, and a port to the underdrive control cylinder. The groove between valve stem lands is opposite the port carrying charge oil. When output speed of the drive varies from the set value, as during starting or changes in load, the valve stem moves up or down, porting charge oil to either the underdrive control cylinder or the overdrive control cylinder, and porting the other to drain into the lubrication circuit. When the output speed is correct the valve stem will be positioned so that its lands cover the ports to both control cylinders, and the pump wobbler will be held in position.

Load Sharing

'Real' load sharing between paralleled alternators and drives is accomplished by automatically adjusting the spring bias of the governor control associated with each drive. The spring bias is adjusted by means of a small geared 2-phase induction motor which receives signals from a magnetic amplifier controlled by current transformers in each of the alternator circuits.

Table III shows the load division obtained with this arrangement applied to the 40 kVA Package Drive.

Under steady state conditions load sharing within 2 kW is achieved.

Rating

The rating of the 40 kVA Package drive is :—

Full load continuous	50 h.p.
5 minutes intermittent	75 h.p.
5 seconds intermittent	100 h.p.

Performance

A demonstration schedule reproduced as Table IV has been arranged to show the performance of the Sundstrand unit when acting singly and then in parallel, the sequence of operations being as follows :—

One set is started and, with no load, it is shown how the Sundstrand unit is capable of maintaining constant output speed under steady and transient conditions. Electrical loads are then added in various increments and the drive run at different speeds to demonstrate its characteristics. With one set running under load, the second set is started and then run in parallel, and the various duties repeated. Then the two sets are run with one increasing and the other decreasing speed, and at the same time the electrical loads are changed.

Finally, on shutting down, one machine is used to demonstrate the underspeed protection device, which becomes operative when the input speed

TABLE III

LOAD DIVISION BETWEEN PARALLELED ALTERNATORS WITH 40 kVA 'PACKAGE' DRIVE

Input speed	Input speed acceleration or deceleration r.p.m./sec	Drive load kW	Average drive output speed r.p.m.	Total load division between drives
3000-8000	0-50	30	6000±15	within 4 kW
3000-8000	50-600	30	6000±75	within 12 kW
5000-8000	600-1200	30	6000±60	within 14 kW

TABLE IV

DEMONSTRATION SCHEDULE TO SHOW PERFORMANCE OF SUNDSTRAND UNITS

A. SINGLE ALTERNATOR OPERATION

No.	Description	Nominal load kW	kVAr	Input speed r.p.m.	Approx. acceleration and deceleration r.p.m./second
1	Start up engine	—	—	5000	—
2	No-load acceleration and deceleration	—	—	3000 to 8000	500
3	As for (2)	—	—	3000 to 8000	1000
4	Load switching up to 40 kVA ..	8		5000	—
		16	+8kW pulse	5000	—
		16	+ 24	5000	—
		24	+ 24	5000	—
		32	+ 24	5000	—
5	Full-load acceleration and deceleration	32	—	4000 to 8000	500
6	Half-load acceleration and deceleration	16	—	4000 to 8000	500

TABLE IV *Continued*

B. PARALLEL OPERATION

No.	Description	Nominal load total kW	Nominal load total kVAr	Input speeds r.p.m. No. 1	Input speeds r.p.m. No. 2	Approx. acceleration and deceleration r.p.m./second
1	Parallel alternators with load on one only	16	—	5000	5000	—
2	Load switching up to 80 kVA ..	16	—	5000	5000	—
		16	+ 8kW pulse	5000	5000	—
		32	—	5000	5000	—
		32	+ 24	5000	5000	—
		48	+ 24	5000	5000	—
		48	+ 48	5000	5000	—
		64	+ 48	5000	5000	—
3	Full-load acceleration and deceleration	64	—	5000 to 8000	5000	1000
4	Half-load acceleration and deceleration	32	—	5000 to 8000	5000	1000
5	'One-up, one-down'	32	—	8000	4000	—

falls below the minimum governing speed, as in the case of an engine failure.

Other Types of Hydro-mechanical Drive

Cartridge Type

This is fundamentally the same in operation as the Package drive just described, but the unit is designed to be installed as an integral part of the main engine or gearbox and must therefore use engine oil and engine pumping, scavenging and cooling facilities. This particular type of drive has not accumulated the same wealth of running time in service as the Package type.

Radial Piston Types

Other types of drive under development in the U.S.A. include radial piston designs, employing the same differential principle as described in this article.

RECENT 'ENGLISH ELECTRIC' TECHNICAL PAPERS

A Correction

Under this heading in the June 1955 issue of this journal (Vol. 14, No. 2, page 57) reference was made to a paper by Mr. A. R. van C. Warrington on 'Economies in the use of protective relays'. The statement that this paper had been read before the South African Institute of Electrical Engineers was erroneous, and an apology is now made to that Institute.

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